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Task 6, Control Strategy Analysis

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This study developed and evaluated a comprehensive lest of alternative strategies for controlling the ambient air quality impact of residential wood combustion (RWC) in the Pacific Northwest. Over seventy-five control strategy elements were initially evaluated, using a Keppner-Tregoe evaluation process, which included five minimum (MUST) criteria and twelve desirable (WANT) criteria. Twenty generic strategy approaches were evaluated, using available published information an extensive assumptions, to estimate their potential ability to reduce RWC particulate emissions. Based on the findings of these analyses, fifteen RWC control strategies were selected and evaluated using the Keppner-Tregoe process. Rough estimates of implementation costs were made. A matrix summary of the fifteen strategies was prepared showing their relative ranking based on all twelve WANT criteria, their estimated costs, and benefits in terms of estimated particulate emission reduction potential.

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Task 6
Control Strategy Analysis

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EPA 910/9-82-089a	Residential Wood Combustion Study Task 1 - Ambient Air Quality Impact Analysis
EPA 910/9-82-089b	Task 1 - Appendices
EPA 910/9-82-089c	Task 2A - Current & Projected Air Quality Impacts
EPA 910/9-82-089d	Task 2B - Household Information Survey
EPA 910/9-82-089e	Task 3 - Wood Fuel Use Projection
EPA 910/9-82-089f	Task 4 - Technical Analysis of Wood Stoves
EPA 910/9-82-089g	Task 5 - Emissions Testing of Wood Stoves Volumes 1 & 2
EPA 910/9-82-089h	Task 5 - Emissions Testing of Wood Stoves Volumes 3 & 4 (Appendices)
EPA 910/9-82-089i	Task 6 - Control Strategy Analysis
EPA 910/9-82-089j	Task 7 - Indoor Air Quality

RESIDENTIAL WOOD COMBUSTION STUDY

TASK 6

CONTROL STRATEGY ANALYSIS

RESIDENTIAL WOOD COMBUSTION STUDY
TASK 6
CONTROL STRATEGY ANALYSIS

FINAL REPORT

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ABSTRACT

This study developed and evaluated a comprehensive list of alternative strategies for controlling the ambient air quality impact of residential wood combustion (RWC) in the Pacific Northwest. Over seventy-five control strategy elements were initially evaluated, using a Keppner-Tregoe evaluation process, which included five minimum (MUST) criteria and twelve desirable (WANT) criteria. Twenty generic stragegy approaches were evaluated, using available published information and extensive assumptions, to estimate their potential ability to reduce RWC particulate emissions. Based on the findings of these analyses, fifteen RWC control strategies were selected and evaluated using the Keppner-Tregoe process. Rough estimates of implementation costs were made. A matrix summary of the fifteen strategies was prepared showing their relative ranking based on all twelve WANT criteria, their estimated costs, and benefits in terms of estimated particulate emission reduction potential.

EXECUTIVE SUMMARY

The growth in residential wood combustion has been identified as a significant contributor to non-attainment of total suspended particulate ambient standards in several Pacific Northwest cities. Under the Clean Air Act, each State is required to prepare a legally im-lementable plan for bringing each non-complying geographical area into compliance. Traditionally, these State-prepared control strategies for particulate have foccussed on industrial emissions and have been successful in substantially reducing the industrial contributions. Attention now is turning towards possible control of remaining major particulate contributors, including residential wood combustion. Task 6 examines and evaluates possible control strategies to reduce residential wood combustion emissions.

Seventy-five possible control strategies were selected, including those strategies that have been implemented somewhere in the world, those suggested by knowledgeable air pollution control agency personnel, and those suggested by project members. A systematic ranking system was developed using the Keppner-Tregoe evaluation process (see Table A) and each of the 75 control strategies ranked. The fifteen highest ranking strategies were further evaluated as to costs, projected emissions reductions, and significant advantages and disadvantages. Table B describes each of the fifteen strategies, it's ranking and the major advantages and disadvantages. Table C lists the estimated costs and total particulate emission reductions associated with each control strategy.

The ranking and evaluation process necessarily included two major sources of uncertainty. These are the assumptions required to be made because of lack of data (costs and projected emission reductions, for example), and the somewhat subjective values assigned during the ranking process. Projecting the response to public education programs, public acceptance of control strategies, and the political feasibility in passing the necessary laws, were particularly difficult to assess clearly. Any specific control strategy development would require in-depth analysis of local conditions and

TABLE A

Criteria and Weight Factors Used In Keppner-Tregoe Analysis

CRITERIA	WEIGHT FACTOR*
MUST Criteria	
1. Reduce air pollution impacts from RWC	Mandatory
2. Meet legal requirements	Mandatory
3. Widely applicable to RWC equipment or operating practices	Mandatory
4. Must not increase safety hazard	Mandatory
5. Can be implemented within five years, unless long-term benefits great	Mandatory
WANT Criteria	
1. Reduce average RWC emissions/household	13
2. Reduce number of RWC households	13
3. Widely applicable	10
4. Maximum public acceptance	9
5. Discourage worst appliances/practices	9
6. Minimum consumer cost	6
7. Uses proven techrology	5
8. Minimum circumvention of control measure possible	4
9. Maximum agency administrative feasibility	3
10. Encourages innovative technology	2
11. Minimum free market interference	2
12. Promotes conservation/use of renewable resources (except wood)	1

---

* These weight factors were calculated using an analytic tool called "paired comparison". For further details, see Appendix B of the complete report on Task 6.

TABLE B

Description of Most Effective Control Strategies

Strategy Description	Keppner - Tregoe		Major Advantage(s)	Major Disadvantage(s)
	Rank[1]	Points		
Mandatory testing/certification of all new wood stoves, with only clean burning stoves allowed to be sold. Tax credit (rebate) of $400 to purchaser.	1	535	Significant emissions reduction	Expensive
Mandatory testing/certification of all new wood stoves, with only clean burning stoves allowed to be sold. No tax credit.	2	508	Significant emissions reduction; less expensive than above strategy	Lack of public acceptance due to higher stove costs.
Encourage use of larger firewood piece size through public education	3	490	Inexpensive; public acceptance expected to be high since bigger pieces mean less work splitting wood	None
Mandatory testing and labeling of all new wood stoves by pollution and efficiency levels, but all stoves can be sold. Tax credit for cleaner units.	4	469	Substantial public acceptance expected; significant emissions reductions (but less than when only clean stoves are sold)	Expensive
Encourage use of other fuels by reducing costs of conventional fuels, encourage solar energy use, restrict availability of wood.	5	458	Technology available	Encourageing oil use contrary to federal policy. Poor public acceptance for restricting wood supplies. Other heating sources may not be available or maybe too expensive.

[1] Refer to text for explanation of assumptions used during ranking process.

TABLE B (Cont.)

Strategy Description	Keppner - Tregoe		Major Advantage(s)	Major Disadvantage(s)
	Rank[1]	Points		
Government funded research and development of improved equipment, operating procedures, and testing methods.	6	445	The lack of data currently hampering efforts to evaluate control efforts and stove design/operating procedures will be deminished.	Specific emissions reductions are not quantifiable
Promote proper sizing of new wood burning units of public education and requiring appropriate labeling of new units. Could limit size with building permit restriction.	7	443	Minor cost, good public acceptance. Reduction of creosote and fire problems	Slight user inconvenience in that more frequent charging of smaller units will be required
Mandatory testing and labeling of all new wood stoves by pollution and efficiency levels, but all stoves can be sold. No tax credits.	8	438	Good public acceptance	None
Mandatory weatherization of all households to a cost effective level (fuel savings greater than expense).	9	432	Energy conservation for all fuels	Public resistance, expensive
Stove testing and rating by Trade Association.	10	422	High public acceptance.	Totally voluntary, relies on vigorous implementation by Trade Associaiton with minimal return for Trade Association

TABLE B (Cont.)

Strategy Description	Keppner - Tregoe		Major Advantage(s)	Major Disadvantage(s)
	Rank[1]	Points		
Mandatory weatherization for households buying new or replacement wood burning devices to a cost effective level.	11	411	Will discourage new woodburning units	May be perceived as unfairly affecting one group of people. Expensive
Encourage burning of drier firewood by public education, restricting firewood gathering to as far in advance of heating season as possible, and require firewood suppliers to state moisture content.	12	400	Minimal cost. Potential for substantial decrease in emissions	Public resistance to restricting times of firewood gathering
Voluntary curtailment of RWC during air pollution episodes. Mandatory curtailment required if voluntary curtailment does not work.	13	381	Minimal cost. Reduction of emissions during periods of worst air pollution	Dependent on public cooperation. Effect on annual attainment of standards unknown
Annual inspection and maintenance of woodburning units, including cleaning chimney.	14	321	Will encourage replacement of catalysts at appropriate times; substantial safety benefits expected	Extremely high resistance from public; high expense
Require underfire air for new fireplaces (building code or ordinance).	15	292	Inexpensive, substantial reduction in fireplace emissions	Fireplaces will be used less in future, be a relatively small proportion of emissions

TABLE C*

Summary of Estimated Costs and Particulate Emissions Reduction Benefits for Fifteen RWC Emission Control Strategies

Control Strategy	Costs										
	Start-up	Admin./Year	Other	1985*	1990	1995	2000	1985*	1990	1995	2000
1. Mandatory testing/certification, tax credit	$ 50,000	$130,000	$400/unit tax credit	3	11	30	39	$180,000/%[a]	$48,600/%[a]	$17,800/%[a]	$13,700/%[a]
2. Mandatory testing/certification, no tax credit	$ 50,000	$130,000	---	2	8	22	30	$ 70,000/%	$16,900/%	$ 6,100/%	$ 4,400/%
3. Encourage use of larger pieces of firewood	---	$ 45,000	---	11.5	11.5	11.5	11.5	$ 3,900/%	$ 3,900/%	$ 3,900/%	$ 3,900/%
4. Mandatory testing/labeling, tax credit for cleaner units	$ 50,000	$160,000	$400/unit tax credit	1	5	15	21	$570,000/%[a]	$113;000/%[a]	$37,500/%[a]	$16,800/%[a]
5. Encourage use of other fuels and energy sources	UNKNOWN										
6. Government funded research and development	UNKNOWN										
7. Promote proper sizing of wood stoves	---	$ 45,000	---	--	7	--	10.5	---	$ 6,400/%	---	$ 4,300/%
8. Mandatory testing/labeling, no tax credit	$ 50,000	$130,000	---	1	3	8	11	$140,000/%	$ 45,000/%	$16,700/%	$12,000/%
9. Mandatory weatherization - all households. Cost effective	---	$150,000	$1450 per household	--	3.5	16.4	--	---	$ 9,100/%[b]	$21,400/%[b]	---
10. Stove testing/rating by Trade Association	$ 50,000	$130,000[c]	---	1	3	8	11	$140,000/%	$ 45,000/%	$16,700/%	$12,000/%
11. Mandatory cost effective weatherization - new or replacement RWC households	---	$ 50,000	$1450 per household	--	3.5	7.0	--	---	$ 14,300/%[b]	$ 7,100/%[b]	---
12. Encourage burning of dry firewood	---	$ 45,000	---	6.2	6.2	6.2	6.2	$ 7,300/%	$ 7,300/%	$ 7,300/%	$ 7,300/%
13. Curtailment of RWC during air pollution episodes	$ 25,000	$ 8,000	---	33[d]	33[d]	33[d]	33[d]	$ 400/%[d]	$ 400/%[d]	$ 400/%[d]	$ 400/%[d]
14. Annual inspection/maintenance of installed units	---	$1,000,003	---	UNKNOWN							
15. Require underfire air for new fireplaces	---	$200,000	---	--	1	--	2	---	$200,000/%	---	$100,000/%

* Assume 1980 as base year.

[a] Assume 1000 new wood stoves/year.

[b] Fuel savings exceed cost of weatherization. Annual costs only for administrative expenses.

[c] Costs paid by private sector.

[d] Reduces particulate emissions only during episodes. Effect on annual TSP levels unknown.

* Refer to text for discussion of assumptions used in arriving at estimated costs and particulate reductions.

re-evaluation of these control strategies. However, this study should assist control agency personnel in the initial selection of possible control strategies for further evaluation.

Best Emissions Reductions

The two strategies which ranked highest also provide the highest percentage reduction in RWC particulate emissions -- 39% and 30% respectively, by the year 2000. Both involve mandatory testing/certification and prohibition of the sale of wood stove/furnace models which can't comply with government emission standards ($\leq$5 g/kg suggested standard).

This strategy approach is very effective over time in lowering emissions, as these new units replace existing stoves/furnaces which emit, on the average, four times as much particulate pollution. This approach requires years for its maximum benefits to accummulate.

Both strategies restrict consumer choices dramatically, which could produce public opposition, if such limitations are perceived to have caused the price of remaining stoves to rise unreasonably. To help avoid this, the top ranked strategy includes a financial incentive (33% tax credit estimated at $400/unit in 1984). This in turn makes this the most expensive strategy of all those reviewed, with likely annual costs (tax revenues foregone) in the millions of dollars for a program on statewide scope.

Such costs appear to be appropriate and manageable. For example, Oregon has spent hundreds of millions of dollars over the last decade in pollution control tax credits for industrial control equipment. The growing evidence that RWC particulate emissions approach or surpass those of industrial sources in many cases (e.g., Portland, Oregon) argues strongly for shifting some pollution control tax credit resources to address RWC.

Another potential hurdle in implementing the testing/certification approach are possible difficulties in enacting legal authority to prohibit commercial sales of non-certified burning units.

Least Cost Emission Reductions

Based on the analyses and assumptions in this report, a group of strategies emerge which potentially offer significant RWC emissions reductions, with minimal cost and inconvenience, and high public acceptance. The strategies with their estimated RWC emissions reductions in parenthesis include: encouraging larger firewood piece size (11.5%), encouraging use of firewood with an appropriate moisture content (6.2%), encouraging use of properly sized stoves (7-10%), and voluntary episode controls (33% or more on episode days). All are based on public education. The first three could be implemented jointly with annual administrative costs that are modest (estimated less than $100,000 in Appendix F). The combined emissions reductions of these three strategies is 23% by about 1990 [(1.0 - .062)(1.0 - .115)(1.0 - .07) = .77].

However, it should be noted that the equations used to estimate emissions reductions from all three strategies are based on limited lab tests by a single researcher (different in each case), although the general phenomena may have been observed by several reseachers. These strategies are thus prime candidates for further research to determine whether they really do offer the most cost-effective RWC controls.

Research and Development

Despite the fact that no emission reduction estimate could be made for this strategy, it still ranked highly (5th overall) in the Keppner-Tregoe process. It is the key which could open the door to emission reductions from a wide range of strategies. This point is illustrated in the section above which discusses educational strategies to change operating practices. These strategies may well be the most cost-effective strategies for reducing RWC emissions over the next 10-20 years, but additional research is needed to verify this and to evaluate improvements in stove operation and design.

Of all research and development funding categories, the greatest need appears to be for the development of simpler and less expensive emission measurement techniques for RWC. This not only would facilitate testing/certification and testing/labeling strategies, but would also help researchers evaluate how RWC emissions are affected by key variables such as moisture content, piece size, and charge size.

Emissions Testing/Labeling Strategies

Three strategies requiring testing/labeling of woodburning devices for efficiency and emissions ranked 4th, 8th, and 11th respectively in the overall ranking. All offer potential significant emissions reductions by 1990 - 2000. The largest reduction occurs with a significant financial incentive (33% tax credit) which also greatly increases the program costs.

The emissions reduction benefits are significantly less than those from Strategies #1 and #2 which restricted sales to clean burning units only. The dramatic limitation on consumer choice was at once a major strength and liability for the testing/certification strategies. The three-testing/labeling strategies preserve consumer choice. In so doing they are likely to be much less effective in promoting the purchase and installation of stoves emitting <5 g/kg. Even with the tax credit option, there are likely to be cheaper stoves available with much poorer emission characteristics.

Weatherization

The two weatherization strategies (mandatory weatherization for all households and mandatory weatherization only for households purchasing new stoves) were ranked 9th and 12th. Both were judged to have relatively poor public acceptance due to their mandatory nature, and high initial cost (despite eventual "payback" through fuel savings).

In the short-term, weatherization of a household does not yield an emission reduction equivalent to the reduction in heat (BTU) requirements, because 1) the operator may continue to burn as much wood as before and rely less on conventional fuels, 2) the operator may burn at a slower burn rate with a higher emission factor, and 3) most operators will not immediately replace their existing stove with a smaller less-polluting unit. Most of the short-term reduction is due to burning on fewer days since better insulated houses have to be heated on fewer days.

In the longer term, when the owner of a weatherized home replaces his existing stove, additional emission reduction benefits may occur, if an education program cnoviences him to purchase a smaller stove, which can be operated in a manner that generates lower particulate emissions.

Public Acceptance

The strategies rated most acceptable to the public at large and to RWC households in particular generally were those involving the least inconvenience and/or costs. For example, the strategy encouraging larger firewood piece size ranked third overall, with the highest possible scores in "public acceptance" and "minimizing consumer costs". It costs individuals nothing, and reduces the work of splitting wood, while affording significant (11.5%) estimated emissions reductions.

The labeling strategies ranked next highest in public acceptance. They provide information which helps the consumer choose a new stove, without limiting his choices or raising stove prices. The version with a subsidy (tax credit) ranked highest of these three.

Ranking similarly high in public acceptance were encouraging use of low moisture firewood and proper stove sizing. Both provide information and rely on voluntary compliance with little or no enforcement pressures (stove sizing could involve an installation permit review process). Episode controls which ranks almost as high in public acceptance, also would rely on voluntary compliance except under very severe pollution levels. Research and development easily ranks high in public acceptance, offending no one.

no one.

Lowest Ranked Strategies

The strategies which ranked last under the Keppner-Tregoe analysis were fireplace underfire air and periodic inspection. Fireplace underfire air has been reported to reduce emissions by 40%, but this is based on a single lab test. This strategy does not address the largest category of RWC emissions at all -- stove emissions -- and it applies only to new fireplaces. It was not assumed to have high public acceptance.

Periodic inspection, although it has significant safety benefits, was not assumed to have any certain emission reduction benefits in most cases. The inspection strategy appeared likely to have emission reduction potential only in areas with either 1) a high fraction of catalyst stoves (catalyst lifetimes are about two years), 2) a high fraction of new technology high efficiency units (more sophisticated units may be more likely to need maintenance to maintain high performance), or 3) a limited number of stove models, since inspections then would have greater potential for recognizing relatively poor performance and maintenance needs. Periodic inspections were assumed to have poor public acceptance.

Stove Modifications or Add-on Devices for Existing Stoves

This area of emission reduction was initially evaluated but was not included in the more detailed analysis for several reasons. Data generally is lacking or not conclusive in supporting the effectiveness of add-on devices (such as catalysts) or stove modifications (such as lining stoves with firebrick). Other concerns included the cost, and the long-term effectiveness of control measures.

Zoning Restrictions Prohibiting New Wood Stoves in Specific Areas

This approach has been used in other areas, but was rejected for the Pacific Northwest because of the expected and insurmountable public resistance.

I. INTRODUCTION

This section describes: the purpose of the analyses conducted under Task 6 (Section A); a summary of the technical approach used in selecting and evaluating control strategies (Section B); and, an overview of the organization of the rest of this report (Section C).

A. PURPOSE

The primary purpose of Task 6 is to develop and evaluate a comprehensive list of reasonable alternative strategies which could be applied in the Pacific Northwest to control the ambient air quality impact of residential wood combustion (RWC).

Many potential RWC controls were considered, including some which are admittedly costly, politically controversial, or otherwise difficult to implement. The intent was to be as comprehensive as reasonably possible in the selection of control strategy elements for initial evaluation. The ultimate objective was to evaluate a list of RWC control strategies which represented the major options for controlling RWC pollution available today.

It was emphatically not the intent of this study to discourage RWC per se, but rather to identify the most potentially effective ways to minimize its pollution impact. This should be remembered when reviewing the (Keppner-Tregoe) evaluation process itself, which contains criteria that may, at first glance, appear to be supportive of such outcomes as "reducing the number of RWC households". This criteria seemed fundamentally appropriate in evaluating the potential effects of a given strategy - asking in effect, "to what extent will this strategy discourage new RWC households, or encourage existing RWC households to discontinue RWC?" Also only one of the final strategies considered was designed to intentionally reduce the number of RWC households, by encouraging use of conventional fuels like, oil, gas, and electricity. This too seemed a necessary inclusion in any comprehensive consideration of RWC control strategies.

B. SUMMARY OF TECHNICAL APPROACH

Leading examples of RWC control strategies implemented elsewhere were researched and described, using literature reviews and personal contacts with knowledgeable individuals.

Based on the information obtained from all sources, an initial list of about 75 potential control strategy elements was assembled (Appendix A). A number of these were not necessarily considered feasible, but were included for comprehensiveness. The strategies considered were grouped in the following categories:

1. Strategies to reduce emissions by improved burning unit design;
2. Strategies to reduce emissions by reducing wood usage, and;
3. Strategies to reduce emissions by improving on operating procedures for wood burning appliances.

Within these categories, strategies were organized by methods of achieving the strategies, including:

1. Regulations requiring compliance with various wood burning rules.
2. Market incentives to achieve the strategies.
3. Information distribution/technology transfer to speed development and implementation of strategies.

The Keppner-Tregoe decision analysis process was used to evaluate and rank the comprehensive list of proposed strategy elements. For this process, MUST and WANT criteria were developed, which represented strategy characteristics considered essential and desirable, respectively. WANT criteria were weighted according to their relative importance, using a method of paired comparison.

The full Keppner-Tregoe evaluation consisted of three steps. First, strategy elements which did not satisfy all MUST criteria were eliminated from further consideration. Second, each strategy element was rated on a scale of 1 - 10 as to how well it satisfied each WANT criteria. Each rating was multiplied by the weighting factor for that WANT criteria. The resulting scores were summed over all WANT criteria to give a total score reflecting how well each strategy element satisfied all of the WANT criteria, simultaneously. These total scores constituted a preliminary ranking of all the strategy elements as to which were the most effective, practical and publicly acceptable.

The third step in the Keppner-Tregoe process evaluated possible adverse consequences of implementing a given strategy, generating an "adverse consequence score", or risk factor. This involved estimating on a scale of 1 - 10, both the likelihood of occurrence and the seriousness of the adverse impact; and then multiplying the two numbers to obtain an adverse consequences score. Adverse consequences scores also were summed for each strategy considered, but they were not subtracted from the scores based on satisfaction of WANT criteria. Instead, their magnitude is noted, and a common sense judgement made as to whether the adverse consequences were serious enough to warrant changes in the preliminary ranking of strategies.

The initial comprehensive list of individual strategy elements was evaluated using only the first two steps of the Keppner-Tregoe process - i.e., without considering risk factors. Those strategy elements which ranked high were given further consideration for inclusion in the final list of RWC strategies evaluated.

A second analytical approach to selecting strategies for final evaluation involved consideration of a list of twenty generic strategy approaches - i.e., basic general ways to reduce RWC emissions, such as improving (decreasing) burning unit emission rates, weatherizing homes to reduce space heating requirements, wood moisture control, etc.. Rough estimates were developed of the potential (particulate) emissions reductions achievable by these strategy approaches. A summary table of relative emissions reduction potential was prepared.

These particular analyses were often speculative due to scarcity of emissions test data, and the need to estimate variables such as

"What fraction of the public would be induced to reduce their firewood moisture content by improving their wood storage practices?" However, despite the many assumptions required, this analysis proved valuable in requiring examination of available test data and fundamental theories of wood combustion, in order to estimate possible emission reductions quantitatively.

Based on all these analyses, a list of fifteen final RWC control strategies was prepared, which was intended to represent a reasonably comprehensive range of control options available to regulatory agencies. Some of the final strategies were patterned after strategies implemented in an actual city or region. Major elements of the final strategies were selected because of their relatively high estimated emission reduction potential,or a high ranking in the initial Keppner-Tregoe evaluation of strategy elements, or a combination of such considerations. The final strategies selected were kept simple, to enable the final Keppner-Tregoe analysis to evaluate and rank a range of clearly discreet approaches.

Costs and benefits of the final strategies also were estimated and compared. Dollar costs, to both public and private sectors, of implementing each strategy or category of similar strategies, were considered separately, although cost factors also were included in some of the WANT criteria used. The types of costs considered included: 1) public sector: agency costs to implement a strategy; public costs to comply with regulatory requirements, or increased consumer costs for wood burning caused by strategies; and 2) private sector: costs to comply with regulatory requirements, or to take advantage of incentives or meet competition caused by strategies. These cost estimates are admittedly rough, but their assumptions and uncertainties are spelled out, as much as possible. They also were based where possible on the experience of established control programs. Any significant benefits associated with particular strategies, in particular to their effects on RWC emissions also were considered separately, e.g., any improvement in safety factors associated with wood burning as a result of a strategy to control pollution. Some benefits such as promotion of energy conservation, are built into WANT criteria in the evaluation process.

A full (3-step) Keppner-Tregoe analysis was performed on the final fifteen strategies. The result was a final overall ranking of the fifteen strategies based on all twelve WANT criteria. This ranking was displayed in matrix format along with the costs and benefits identified for each strategy. The matrix summarizes the information developed in this analysis on the relative ability of these fifteen strategies to reduce RWC air quality impacts with maximum effectiveness, practicality and public acceptance, and minimum cost and adverse consequences. Narrative findings and conclusions also are presented.

C. OVERVIEW OF REPORT

The remainder of this report is organized as follows:

- Section II describes leading examples of control strategies implemented to reduce the air pollution impacts of residential space heating.
- Section III describes the Keppner-Tregoe process as it was adapted to evaluate RWC control strategies. This includes descriptions of the selection of MUST and WANT criteria, and the determination of weighting factors for WANT criteria.
- Section IV describes the comprehensive initial list of seventy-five RWC control strategy elements and its evaluation using an abbreviated Keppner-Tregoe process.
- Section V describes the quantitative estimates of RWC emission reductions achievable by twenty generic strategy approaches.

- Section VI describes the selection and evaluation of fifteen final RWC control strategies, using the full Keppner-Tregoe process, including the matrix summary of their final ranking, costs, and benefits.
- Section VII lists information sources used in this study (References).

- Appendix A describes details of the Keppner-Tregoe process.
- Appendix B describes the individual RWC control strategy elements selected for evaluation.
- Appendix C describes and documents the ranking of control strategy elements, including the Keppner-Tregoe scores of each strategy element versus each WANT criteria.
- Appendix D describes the assumptions and rationale behind the quantitative estimates of emission reduction potential of generic RWC control strategy approaches.
- Appendix E describes and documents the Keppner-Tregoe evaluation and ranking of the final fifteen RWC control strategies.
- Appendix F describes and estimates the costs associated with implementation of the final RWC control strategies; selected benefits also are discussed.

II. LEADING EXAMPLES OF CONTROL STRATEGIES IMPLEMENTED TO REDUCE AIR POLLUTION IMPACTS OF RESIDENTIAL SPACE HEATING

This section describes leading examples of control strategies implemented in various places in the world to abate air pollution problems from residential space heating. Some of these approaches were designed to address air pollution problems arising from the use of solid fuels, such as coal or wood. Other programs were more general in that they were concerned with any home heating equipment based on fuel combustion. Some also were concerned not only with air pollution emissions, but also safety factors, and the overall energy efficiency of home heating equipment. This points up the fact that some basic RWC control strategy elements - e.g., weatherization, or inspection of home heating devices - inherently have broader objectives and benefits than pollution control alone. Control of RWC pollution problems may best be accomplished in efforts which combine the objectives and resources of programs concerned with environmental quality, fire safety, and energy conservation.

The following descriptions of control programs are not exhaustive. It presents leading examples of different approaches tried in various countries to address a variety of situations. The descriptions focus on the general types of regulatory actions, incentives and public information methods employed which could be used or adopted for control of RWC air pollution impacts in this country. The reader is encouraged to consult the references provided for additional details on these programs.

A. GREAT BRITAIN[1f]

During a 1952 London "fog" episode, 4000 deaths were attributed to high sulfur dioxide and particulate pollution from residential coal burning. This prompted the British government to establish a control program through a 1956 British Clean Air Act which included the following elements:

- Establishment of Smoke Control Areas in densely populated urban centers with heavy coal burning.
- In these areas, residential coal burning which produced smoke was prohibited. Burning was allowed only with "smokeless" (low smoke) stoves or smokeless (low volatiles) fuels. These were rated by specific British standards, based on testing by a British nationalized firm, the National Coal Board.
- A 70% rebate on the cost of a smokeless replacement coal stove was subsidized by the British government. Additional subsidies were available in the case of extreme economic hardship.

Since 1956, over fifteen coal-based smokeless fuels and eleven smokeless coal stoves have been certified for use in smoke control areas. Today, London has 70% greater December sunshine, better winter visibility, and reduced labor and expense for laundry and house cleaning. Active government involvement, and the stove and fuel performance rating system and standards, encouraged significant technological improvements to occur in a relatively short time. The 70% subsidies unquestionably accelerated use of the improved stoves and fuels.

The standardized emissions test methods developed for coal do not capture and measure much of the condensible organic emissions. This is an especially important weakness related to RWC, since most RWC emissions are organic.

B. NEW ZEALAND[1b]

Calm winter nights, and widespread burning of indigenous coal or wood fuels for domestic heating, contribute heavily to air pollution levels in New Zealand cities. For example, in New Zealand's largest city (Christchurch) winter smoke levels frequently exceed the World Health Organization's recommended goal of 100-150 $\mu g/m^3$. (New Zealand has no ambient air quality standards.) Cleaner burning fuels such as oil and gas are costly and less available. The government of New Zealand has decided that people should retain the option to burn local coal and wood fuels, and has implemented measures to help reduce its adverse air pollution impacts.

New Zealand's 1972 Clean Air Act established air pollution control requirements for both industrial and domestic sources. Patterned closely on the 1956 British Clean Air Act, the New Zealand Act authorizes local governments to establish Clean Air Zones to control domestic smoke pollution. Within these zones the local government can apply in total or in part the following Clean Air Zone provisions:

- Only approved domestic fuel burning equipment may be installed as new or replacement units.
- Acceptable fuels may be prescribed - e.g., the sulfur content of domestically burned coal must be $\leq 0.5\%$.
- Acceptable installation and/or operating practices for domestic fuel burning equipment may be prescribed - e.g., whether stoves may be banked ("airtight" operating conditions) for overnight operation.

To date only Christchurch City Council has implemented Clean Air Zones, and has applied their provisions only to new and voluntary replacement units. No subsidy is available to encourage replacement with cleaner units.

Standardized testing of appliances under various burning procedures is necessary to support this regulatory system. This was initially done (until 1980) by the privately funded Coal Research Association, in cooperation with a government control agency (Department of Scientific and Industrial Research). British testing procedures, modified to suit New Zealand fuels and conditions are used. Because wood burning appliances have increased their competition with coal burning appliances, an independent laboratory recently has been contracted for the standardized testing used for type-approval of heaters. Also a different government agency (Department of Health) has set up test facilities for basic research to develop cleaner burning equipment and/or fuels.

Since 1980 wood burning appliances have proliferated in a domestic market previously dominated by coal burners, and three have been approved for use in Clean Air Zones. The small market in New Zealand has so far precluded development of smokeless fuels at an economic cost, so emphasis has been placed on developing cleaner combustion equipment. The Department of Health has developed two low smoke wood stoves, whose key design features include 1) maintenance of high temperature in firebox and afterburner chamber, by using adequate refractory (firebrick); and 2) an adequate supply of pre-heated secondary air, and turbulent mixing, to produce more complete combustion of volatile organics. New Zealand researchers believe wood can burn more cleanly than coal in well designed domestic heaters.

C. EUROPEAN EXPERIENCE[1c, 1f]

Severe air pollution problems from wood burning are not common in Europe, usually occurring in mountain valleys prone to atmospheric inversions which heavily depend on wood for domestic heating, and near wood processing facilities which burn wood wastes. Wood is not plentiful in Europe - especially for densely populated cities. To obtain maximum heat output from this scarce fuel, Europeans tend to use high efficiency combustion equipment, and seasoned wood, both of which tend to reduce emissions. Considerable residential heating in cities also is done by block or central district heating plants, which results in fewer, more efficient and less polluting combustion units. Nevertheless, there is renewed concern about pollution with increasing domestic combustion of wood, alone or combined with other fuels like coal, as alternatives to imported oil and gas fuels are increasingly sought.

While regulation of combustion sources of home heating in Europe has taken diverse forms, the central focus had been on residential equipment design, installation, operating and maintenance. Most European countries have regulations requiring inspection and maintenance of block and central district scale heating equipment, at least once a year by professional chimney sweeps. These inspections typically check not only pollutant emissions, but also safety and efficiency factors; and clean and adjust the equipment and chimney for optimum performance. Such inspection and maintenance is not typically required for residential scale equipment except under local nuisance procedures when complaints are received. Solid fuel fired residential scale equipment is often unregulated, although there is growing interest in it, as wood and coal fuel becomes increasingly attractive.

For example, in West Germany federal law requires that residential scale heating devices fired with solid fuels must either: 1) use smokeless (low smoke) fuels; or 2) be designed like a Universal-Dauerbrenner (slow combustion) stove, which achieves more complete combustion of volatiles during a down draft design, which forces volatiles to pass through a flame zone before exiting from the burner. Inspection of residential scale solid fuel-fired heating equipment is not required unless complaints exist. Larger (block or central district heating) equipment must be inspected by the district chimney sweep once a year, including an emission test measurement. For some of the larger equipment, specific particulate emission standards exist.

In Switzerland, no federal environmental protection law exists, so legal enforcement of emissions limits only could be done through nuisance complaints. No emission standards exist for solid fuel fired equipment. A federal guideline prohibits trash burning in fireplaces, and recommends burning dry wood only. Fire insurance companies require testing of any heating appliance, mostly for safety factors. However, carbon monoxide emissions are limited to 1% by volume for solid fuel fired equipment. Larger central heating plants must have annual inspection and maintenance by chimney sweeps. Austria, like Switzerland, has relied on required maintenance of larger heating equipment rather than emissions standards.

In Sweden[1a] a large increase in RWC has occurred in the last few years - especially in areas with electric heating. Rising citizen complaints and studies showing significant emissions of benzene and polycyclic aromatic hydrocarbons (PAH) from wood combustion, have prompted Swedish authorities to study the adoption of new performance standards for all sizes of wood combustion furnaces. By 1983, formal requirements for solid fuel fired residential heating equipment are expected to be proposed for inclusion in the Swedish Building Code, which regulates all combustion heating equipment. This code currently contains no guidelines for solid fuel combustion. The new requirements are expected to include:

- Minimum distance between the chimney serving RWC equipment and the nearest house (probably 15-30 meters). Exemptions may be likely for aesthetic fireplaces but not for stoves for heating.
- Recommended RWC equipment operating procedures, including:
  - Do not burn certain wastes, including paper
  - Always burn dry wood
  - Do not excessively restrict air supply
- Design type or emissions standards for small, residential scale wood burning furnaces, possibly based on carbon monoxide emissions.

A primary concern in Sweden is that residential wood combustion, using common existing stoves and heaters, could cause long-term ambient PAH and benzene concentrations comparable to or several times worse than Swedish urban areas with high traffic density.

Sweden strongly promotes central district heating systems which presently supply 25% of space heating needs. They also have a much less negative impact on air quality in urban and suburban areas, by taking advantage of the fact that fewer large fuel combustion systems can be operated more efficiently and far more cleanly than many small ones in individual homes. Pollution control equipment can be applied to the larger units with economies of scale not possible for individual home units.

Denmark has limited wood available for RWC and no standards for wood combustion equipment.

France has abundant forest resources, and great potential for expanding its use of wood as a fuel. France has not regulated domestic solid fuel combustion, except for a few local prohibitions of wood or coal use in clean air zones of some of its larger cities. Fire insurance companies in Paris increase premiums up to three fold for failure to provide evidence of annual inspection and maintenance.

D. ROCKY MOUNTAIN REGION, U.S.A.[1d]

Several Colorado mountain communities (Vail, Aspen, Telluride, Steamboat Springs) were concerned that increasing tourism, in which they were economically interested, would worsen already declining air quality, primarily due to increased fireplace use and automobile traffic. For example, the following control measures were implemented in Vail, Colorado:

- Public education - how to burn cleanly
- Voluntary curtailment of RWC and driving is requested when CO or TSP exceed specified levels
- New homes, hotels, and restaurants are prohibited from installing more than one stove or fireplace
- Coal sale or use is banned in the city limits (although not in the surrounding county were most growth is occurring).
- Devices to improve fireplace efficiency (e.g., excess air) are required
- The City Engineer may establish design standards for RWC equipment.

The city of Missoula, Montana, located in one of the poorest ventilated areas in the country, has high RWC activity levels and violations of federal CO and TSP ambient air quality standards. RWC was confirmed to be a major source. As a result, citizen committees recommended the following RWC control measures[10] in 1981:

- Public education on potential RWC impacts
- Voluntary curtailment of RWC and driving requested by media "alert", when TSP exceeds 150 $\mu g/m^3$ (or 60 $\mu g/m^3$ of respirable particulates).
- As of January 1982, mandatory curtailment of wood burning when TSP exceeds 300 $\mu g/m^3$ on an 8-hour basis (since adopted).
- Establish emission standards for RWC equipment in new construction.

Technical problems may preclude implementation of some of those recommendations. The cost/benefit ratio of training smoke readers to conduct opacity tests, or of establishing and enforcing emissions standards, is questioned by EPA.[1d] EPA contends that it lacks authority under the Clean Air Act to establish national emission standards for RWC equipment, similar to those proposed by the Missoula citizens committee, and that such standards may succeed only in promoting distributors to sell their equipment elsewhere, rather than to improve it. To the extent that EPA lacks the authority, or desire to regulate RWC, the most likely areas for development of RWC controls will be communities like Missoula, Montana or Medford, Oregon, which experience major RWC impacts, usually because of high RWC levels and unfavorable meteorological or topographical conditions for pollutant dispersal. Local community emissions or ambient standards would not be precluded, even where state law exempts residential heating from pollution control regulation by state agencies.

E. MEDFORD, OREGON

Medford, Oregon also is situated in a mountain valley with atmospheric inversions similar to Missoula, Montana in its capacity to trap and concentrate air pollutant emissions. Studies by the Oregon Department of Environmental Quality (DEQ) have used chemical mass balance analysis to measure respirable particulate and have measured impacts from RWC of as high as 82 $\mu g/m^3$ during poor winter ventilation periods. Annual average impacts of 20.6 $\mu g/m^3$ of respirable particulate from RWC were recorded in downtown Medford for a July 1979 - June 1980 period. This accounted for 29% of all locally generated total particulate and 66% of all locally generated (i.e., corrected for background levels) respirable particulate.[1f] It is clearly the major particulate source impacting the Medford area, which currently violates primary (health related) particulate standards.

The Jackson County Commission with planning jurisdiction for the entire valley containing Medford and nearby smaller towns, recently adopted the following RWC control strategy[2], aimed at eliminating primary standard violations by July 1984:

- Firewood Moisture Control - through public education about seasoning wood; and encouraging spring firewood cutting at nearby national forests, through incentives to individuals and commercial cutters.
- Weatherization - required, to minimum cost effective levels, to install a new wood stove. A voluntary goal was set to weatherize all households in the air quality planning area by July 1984, with financial incentives including low interest loans, tax credits and help from utilities. If the primary particulate standard is not met by July 1984, the County will make weatherization mandatory.
- Episode Controls - Voluntary curtailment of RWC during Air Stagnation Advisories, unless there is no alternative heat source. Mandatory curtailment if TSP exceeds the primary standard (260 $\mu g/m^3$), or during Air Stagnation Advisories, if standard is not met by July 1984.

- Proper Sizing of New Wood Stoves - to household heating requirements to be evaluated during stove permit process.
- All new homes with RWC must have an alternative heat source.
- Public education on proper wood stove operation.
- Urged DEQ to develop certification and testing program for RWC equipment, requiring particulate emissions of ≤ 5 g/kg of fuel burned. Only stoves meeting emissions standards should be saleable in Oregon after July 1984, the Commission urged.

This is one of the most comprehensive and well documented RWC control strategies developed anywhere in the world. It required adoption of a local ordinance for the mandatory weatherization element. The major improvements in particulate air quality are expected to come from the weatherization (48%), moisture control (23%), and episode control (14%) strategy elements.

F. PORTLAND AND EUGENE, OREGON

During a 1978 January day which exceeded particulate standards, RWC impacts were measured at 35 μg/m^3 by Carbon-12/Carbon-14 techniques.[1f] During this (1981) study, RWC impacts of 49 μg/m^3 were measured in a Portland residential area on a moderately cold day during which TSP levels were measured at the same site of 111 μg/m^3. RWC emissions in the Portland area now are estimated to exceed all industrial particulate emissions in the area.[4]

Weatherization of households is assumed to reduce household heating requirements by 40% for the 60% of households which are "poorly weatherized" and reduce total RWC emissions by 7 - 22%, depending on starting assumptions (see Appendix D). Weatherization is expensive for the homeowner, but pays for itself usually in 5-10 years in energy savings. A variety of weatherization programs sponsored by the City of Portland, and local utilities offer no interest, or low interest loans, free home energy audits, and help in doing the work or in locating a constractor to do it. Some loans have delayed payback requirements. Most utility loans are available only to their customers.

The City of Portland adopted in 1979 an Energy Policy which requires that all residences be insulated to cost effective levels prior to resale, starting in 1984. Low interest (8%) loans are available. "Cost effective" is defined as total costs of weatherization and fuel should not exceed fuel costs without weatherization. The mandatory feature is subject to voter approval, and a referendum date has not been set yet. Meanwhile, the program is proceeding on a voluntary basis.[5]

Eugene, Oregon adopted a weatherization ordinance[6] in 1981 which differs from Portland's in that, effective in 1985, weatherization of certain city residences (single family to 4-plex residences built prior to July 1974) is the responsibility of the owner after a change in utility service is requested. This occurs after sale of a residence, or after a rental occupancy change, if the renter pays his own utility costs. The utility works with the new owner (or rental landlord) to determine the costs of insulating to specified levels, helps locate a reputable contractor if needed, inspects and certifies the work, and pays for it. The property owner repays the utility through a zero or low-interest loan, under terms yet to be announced. Exemptions from this mandatory program are available through an appeals process, for hardship, and if requirements can be proven unsafe or not cost - or energy - efficient.

Much of these weatherization costs may be recovered by the utility, and passed back to the property owner, as energy conservation rebates (billing credits) from a regional federal power marketing agency (Bonneville Power Administration), under the terms of the new Regional Power Act.[7] If so, then regional BPA ratepayers will be subsidizing home weatherization, because the energy saved is less costly than that which would be produced by new generating facilities. BPA currently expempts wood heated households from energy conservation rebates.

III. A CONTROL STRATEGY EVALUATION PROCESS

A. THE KEPPNER-TREGOE EVALUATION PROCESS

This section describes how the Keppner-Tregoe decision analysis process[8,9] was adapted to evaluate proposed RWC control strategy elements or final control strategies, and to rank them in terms of their overall satisfaction of multiple criteria. This process involved the following steps:

1. Establish minimum requirements (MUST criteria), which any proposed RWC control strategy must meet to receive further consideration.
2. Establish desirable requirements (WANT criteria), which make any proposed strategy more effective or acceptable.
3. Determine the relative importance of the WANT criteria in evaluating strategies (Weighting Factors).
4. Evaluate proposed strategies using MUST and WANT criteria, in two steps. First, screen out strategies which do not satisfy all MUST criteria. Second, for remaining strategies generate a numerical score by evaluating how well each strategy satisfies each WANT criteria. Use scores to tentatively rank all feasible strategies.
5. Review strategies to identify important adverse consequences of implementing them. If these consequences are serious enough, make changes in the overall ranking of strategies.
6. Separately estimate the costs and benefits of each strategy, to both the private and public sectors.
7. Display the final strategy rankings, costs, and benefits in matrix format.

B. SELECTION OF MUST AND WANT CRITERIA

In establishing MUST and WANT criteria, the following considerations were paramount:

1. Proposed RWC control strategies must be effective in reducing air pollutant emissions from RWC activity. This is the first priority.
2. Strategies also must:
   - a. Meet Clean Air Act and EPA requirements.
   - b. Conform to and support State Implementation Plan (SIP) strategies.
   - c. Be widely applicable to RWC appliances or practices.
   - d. Be implementable within a reasonable time (preferably within a few years).
   - e. Not worsen safety characteristics of using RWC to heat homes.
3. Strategies also should, to the maximum extent possible:
   - a. Be technically sound.
   - b. Be administratively feasible.
   - c. Be acceptable to the public.
   - d. Help the RWC appliance industry to itself encourage manufacture of cleaner burning devices.
   - e. Cost parties affected as little as possible.

Tables 1 and 2 summarize the MUST and WANT criteria selected for use in evaluating proposed RWC control strategies. Appendix D describes the rationale for selecting these particular MUST and WANT criteria. The items listed under most WANT criteria help explain their intent, and help apply them in scoring strategies.

TABLE 1
MUST Criteria

1. Reduce RWC air pollution impacts.
2. Meet all legal requirements established by the Clean Air Act, EPA, or State regulations, State Implementation Plans, or local ordinances.
3. Be widely applicable to RWC appliances and/or practices, or be particularly effective for a significant category of RWC appliances or practices.
4. Maintain safety factors of RWC.
5. Be fully implementable within the next five years ... unless significant benefits can be realized over a longer time frame.

TABLE 2

WANT Criteria

1. Reduce the average air pollution (mainly particulate) emissions per household from RWC.
2. Reduce the number of households using RWC.
3. Widely applicable.
4. Maximum public acceptance.
   - -- Minimum hassle to individual (not cost)
   - -- Acceptable level of regulation (i.e., restriction of personal freedom of choice)
   - -- General acceptability to various interests
   - -- Preferably, significant support
5. Discourage use of most polluting RWC appliances/practices.
   - -- Financial disincentives to manufacturers of dirty devices (emissions tax)
   - -- Disincentives for poor RWC practices - create stigma, through media campaign, attached to poor RWC practices ("litterbug" analogy)
6. Minimize cost to individual consumers.
   - -- Capital and operating costs of RWC appliances
   - -- Private sector costs, since these will be passed on to consumers
   - -- Fuel costs
   - -- Financial Incentives - pollution tax credits, rebates, etc.
7. Utilize proven technology.
   - -- Technology demonstrated in practice; minimum research and development needed to implement strategy
   - -- Low maintenance and repairs needed
8. Minimum probability of circumvention.
   - -- Technology based improvements are more guaranteed
   - -- Behavior based improvements are less certain

TABLE 2 (Cont.)

9. Maximum administrative feasibility for regulatory agencies.
   - Minimum agency cost to regulate RWC
   - Implementation ASAP (within 3 - 5 years)
   - Documentable RWC emissions reduction, for SIP purposes
   - Conform to Clean Air Act, EPA requirements
   - Acceptable to regulated parties
   - Other key actors willing to participate
10. Encourage innovative technology.
11. Minimize interference in free markets.
    - Maximum self regulation by RWC appliance manufacturers, retailers, etc.
    - Regulatory policies which try to exert their effect through free market forces, or incentives, will be preferred
12. Promote energy conservation and use of renewable energy resources (excluding promotion of wood fuel for RWC).

C. WEIGHTING FACTORS FOR WANT CRITERIA

To represent the relative importance assigned in this evaluation to each WANT criteria, a Weighting Factor was developed for each criteria. An analytical tool called paired comparison was used for this purpose. The resulting Weight Factors assigned to the twelve WANT criteria are shown in Figure 1. Appendix D explains how these were arrived at. Some of these WANT criteria and their weighting include the following:

1. Criteria which significantly reduce air pollution from RWC are more important than criteria, which are only means to this end. For example, "reducing RWC emissions/household" is directly effective in reducing RWC air pollution impacts. "Use of proven technology" is desirable, but does not guarantee that a strategy will reduce RWC pollutant emissions.
2. The most desirable characteristic of a RWC control strategy is that it reduces average emissions per household. This is a more desirable approach, than reducing the number of RWC households, although both are very effective in reducing RWC pollution impacts. Strategies designed to discourage household use of RWC could be more unpopular, and might unduly limit individual freedom of choice. A widely applicable strategy which reduces average household emissions could improve air quality more than one which discouraged a relatively small portion of households from using RWC.
3. To effectively combat RWC pollution, it is more important that a strategy be widely applicable to RWC appliances, or practices, than low in consumer costs, although both are very important. Wide applicability multiplies any strategy's effectiveness in reducing pollution. Low consumer costs are a strong influence on whether people purchase and continue

to use wood burning appliances, but not all strategies affect appliances, and low price cannot guarantee installation of improved technology.

4. Public acceptance of regulation of RWC, and any extra inconvenience it brings, is very important for an area-wide air pollutant source like RWC. Members of the public who operate these sources can often choose to cooperate or thwart control strategies, as illustrated by public attitudes and actions with respect to vehicle inspections.

D. USE OF MUST AND WANT CRITERIA & RISK FACTORS TO EVALUATE STRATEGIES

MUST and WANT criteria will be applied in a three step process to evaluate the potential feasibility and acceptability of all alternative RWC control strategies proposed. Figure 1 summarizes this process for several hypothetical strategies labeled A, B, C, and D.

In the first step, all proposed strategies are judged against each MUST criteria separately. If any MUST criteria is not substantially satisfied, that strategy is dropped from further consideration. MUST criteria thus serve as "go/no go" criteria in an initial screening step. In Figure 1, Strategy B is eliminated because it did not satisfy all MUST criteria.

In the second step, each remaining strategy is judged against each WANT criteria separately, and assigned a rating of 1 - 10, based on how well it satisfies that criteria. A strategy which completely satisfies a WANT criteria receives a rating of 10, or a lesser rating if it only partially satisfies the criteria. These ratings are multiplied by the weighting factors previously determined, and the sum of these weighted scores is determined for each strategy still under consideration. The summed weighted scores constitute a preliminary ranking of all strategies as to their overall feasibility and acceptability. This ranking will stand unless altered by consideration of Risk Factors in the final step.

FIGURE 1

Application of MUST and WANT Criteria to Evaluate and Rank RWC Strategies

MUST Criteria	Strategy A Go/No Go	Strategy B Go/No Go	Strategy C Go/No Go	Strategy D Go/No Go
1. Reduce RWC Air Pollution Impacts	Go	Go	Go	Go
2. Meet Legal Requirements	Go	Go	Go	Go
3. Widely applicable to RWC appliances or practices	Go	Go	Go	Go
4. Maintain RWC Safety Factors	Go	Go	Go	Go
5. Implementable within 5 years, unless long term benefits great.	Go	Go	Go	Go

WANT Criteria	Weight Factor	Rating	WTD Score	Rating	WTD Score	Rating	WTD Score	Rating	WTD Score
1. Reduce Ave. RWC emissions per household	13	9	117			4	52	9	117
2. Reduce No. of RWC Households	13	9	117			10	130	8	104
3. Widely applicable	10	8	80			4	40	9	90
4. Maximum public acceptance	9	6	54			9	81	7	63
5. Discourage worst appliances, practices	9	4	36			8	72	5	45
6. Minimum consumer cost	6	10	60			7	42	10	60
7. Use proven technology	5	9	45			10	50	9	45
8. Minimize Circumvention	4	4	16			4	16	4	16
9. Maximum agency admin. feasibility	3	10	30			7	21	7	21
10. Encourage Innovative Technology	2	5	10			5	10	5	10
11. Minimum free market interference	2	2	4			7	14	8	16
12. Promote conservation renewable resources (except wood for RWC)	1	0	0			7	7	6	6
WANT Criteria Scores:			563		--		514		593
Adverse Consequences Scores (Risk Factors):			36		--		120		160

In the third step, potential problems of implementation or adverse consequences of fully implementing a strategy are identified. An "adverse consequence score" or Risk Factor is generated by estimating on a scale of 1-10 both the likelihood of occurrence, and the seriousness of the adverse impact. These two numbers are multiplied to provide a score, and the scores are summed to provide a Risk Factor for each strategy as shown in Figure 2. Then these Risk Factor scores are entered in Figure 1 for comparison with WANT criteria scores.

WANT criteria scores then are compared with the adverse consequences scores to determine if the preliminary ranking of control strategies should be changed. Adverse consequences scores are not subtracted from the scores based on satisfaction of WANTs. WANTs and consequences are apples and oranges. Instead, the magnitude of each is simply noted, and a common sense judgement is made as to how they balance out. If the adverse consequences seem serious enough, it may warrant changing the preliminary ranking of overall strategy effectiveness.

Different adverse consequences may be considered for each strategy or the same adverse consequences may be considered for several strategies. Figure 2 provides an example worksheet for considering adverse consequences for hypothetical strategies A, C, and D from Figure 1. Comparison of scores at the bottom of Figure 1 might lead to ranking Strategy A ahead of Strategy D, even though Strategy D had a higher WANT criteria score, because Strategy A had a considerably lower risk factor.

E. COSTS AND BENEFITS

Although cost considerations are included in some WANT criteria (#4, #5), the dollar costs of implementing each strategy (to both the public and private sectors) are estimated to the degree possible in Appendix F. Notable benefits of implementing each strategy are described narratively. Here benefits do not necessarily mean negative

FIGURE 2

Assessment of Possible Adverse Conequences of Strategy Implementation, or Risk Factors

	Probability of Occurrence (P)	Seriousness of Impact (S)	Risk Factor (P x S)
Strategy A			
1. Significant opposition by environmentalists	9	4	36
Adverse Consequences Score (Risk Factor)			36
Strategy C			
1. Key strategy participants unreliable (lending institutions) due to high interest rates	7	8	56
2. Public acceptance questionable because it restricts freedom to sell home	8	8	64
Adverse Consequences Score (Risk Factor)			120
Strategy D			
1. Results very difficult to document	10	7	70
2. Significant opposition by wood stove manufacturers	9	10	90
Adverse Consequences Score (Risk Factor)			160

P = Probability of Occurrence (1 to 10)
S = Seriousness of Impact (1 to 10)
P x S = Risk Factors
10 x 10 = Unavoidable Disaster

costs, but rather bonus achievements from implementing a control strategy, in addition to pollution abatement. An example would be energy conserved by weatherization of homes, or reduced danger of home fires (increased safety) due to reduced creosote formation in stove flues.

The types of costs considered included: 1)public sector: agency costs to implement a strategy; public costs to comply with regulatory requirements, or increased consumer costs for wood burning caused by strategies; and 2) private sector: costs to comply with regulatory requirements, or to take advantage of incentives or meet competition caused by strategies. These cost estimates are admittedly crude, but their assumptions and uncertainties are spelled out, as much as possible. They also were based where possible on the experience of established control programs.

F. MATRIX SUMMARY OF RESULTS

The resulting ranking of control strategies versus WANT criteria may be displayed in a matrix format such as Figure 6 in Section VI of this report, along with highlights of the costs and benefits of implementation.

IV. SELECTION AND EVALUATION OF INITIAL RWC CONTROL STRATEGY ELEMENTS

This section describes the identification and evaluation of a comprehensive list of RWC Control Strategy elements - e.g., single actions which can directly or indirectly help to abate air pollution from residential wood combustion (RWC). These elements were drawn from approaches, regulatory programs, devices or incentives that have been implemented or considered around the world to control RWC pollution. Original ideas for which no precedent was found also are included.

No plausible idea was eliminated at this stage, no matter how potentially costly or difficult it might appear, unless it was simply not widely applicable in controlling wood burning appliances. Consistent with the overall technical approach (Section IB) the identification here of individual RWC control strategy elements for initial exploration is intended to be comprehensive. These strategy elements then are evaluated using an abbreviated (two-step) Keppner-Tregoe process to determine which best satisfy the MUST and WANT criteria described in Section III. A complete ranking of all control strategy elements considered, based on WANT criteria scores, is presented. The reasons why certain elements rank higher than others is discussed.

Over seventy-five individual control strategy elements are identified and evaluated in this section. These were grouped as follows to facilitate their evaluation and to emphasize essential features or distinctions.

- Strategies to reduce RWC emissions by improved burning equipment design.
    A. By regulation
    B. By market incentives, or disincentives
    C. By information distributed, or technology transfer
- Strategies to reduce RWC emissions by reducing wood usage.
    A. By regulation
    B. By market incentives, or disincentives
    C. By information distribution, or technology transfer

- Strategies to reduce RWC emissions by improving operating procedures of wood burning equipment.
    - A. By regulation
    - B. By market incentives, or disincentives
    - B. By information distribution, or technology transfer

A. IDENTIFICATION OF POTENTIAL RWC CONTROL STRATEGY ELEMENTS

Appendix A contains the comprehensive list of potential RWC control strategy elements identified, grouped into the categories listed above. All seventy-five control strategy elements in Appendix A fall into one of the general categories of RWC emissions controls listed below. These were gleaned from literature sources, personal contacts, and our own considerations of RWC emissions control problems and possibilities.

- Weatherization of homes. Reduces space heating requirements. Assumed to reduce RWC emissions by allowing less burning to maintain adequate heating.
- Standardized Emissions Testing of RWC Equipment. Allows objective comparison of burning equipment performance. Provides information basis for consumer choice and feedback to manufacturers to encourage improved performance. Provides basis for emissions standards, and regulations to encourage or require cleaner burning units.
- Wood Fuel Moisture Content Controls. Seasoned (dry) wood burns cleaner under most circumstances.
- Episode Controls. Voluntary or mandatory curtailment of RWC during air stagnations.
- Sizing of Burning Equipment to Space to be Heated. Selecting minimum adequate size minimizes emissions, by minimizing charge size and maximizing burning rate per volume charged.

- Emission Density Zoning. Limiting the amount of RWC in air quality problem areas.
- Periodic Inspection of Installed RWC Equipment.
- Limiting Firewood Supply.
- Promotion of Alternatives to RWC. For example, solar, or other radiant heating appliances, even conventional fuels (oil, gas, electricity); or personal insulation (warmer clothes).
- Economic Incentives or Disincentives, or Public Information. Designed to educate people about RWC and to promote less polluting RWC.
- Research - to Develop Cleaner RWC Equipment or Practices.

B. EVALUATION OF CONTROL STRATEGY ELEMENTS

The Keppner-Tregoe evaluation process described in Section III was applied to the list of RWC control strategy elements in Appendix A, in an abbreviated (two-step) form. That is, strategy elements were evaluated against MUST and WANT criteria, but risk factors related to adverse consquences of implementation were not considered. Risk factors will be considered in evaluating final RWC strategies (Section VI). They should be more meaningful in evaluating final strategies consisting of a combination of strategy elements, because some elements may be employed specifically to mitigate adverse consequences of other elements.

Appendix B contains the seventy-five strategy elements listed in order of their scores based on satisfaction of all twelve WANT criteria. It also contains a table showing the individual scores assigned to each strategy element for each WANT criteria.

The ranking of all strategy elements against all WANT criteria is summarized in Tables 3, 4, and 5 and discussed below. These three tables show the relative ranking of A, B, and C Type control strategy elements, which correspond, respectively, to regulatory actions, market incentives/disincentives, and public information/technology transfer approaches,

TABLE 3

Ranking of RWC Control Strategy Elements
vs
WANT Criteria - Regulatory Actions

Entry	Overall[1]			
	Rank	Score	I.D. No.[2]	Description of RWC Control Strategy
1	1	535	III.A.3	Government requires manufacturer to label stove as space it will heat vs various home insulation levels.
2	2	504	II.A.1.a	Allow new stoves only in highly weatherized households.
3	3	487	I.A.1.a	Government requires certification of new stoves vs emissions standards.
4	4	480	II.A.1.b	Government requires weatherization to cost effective levels within 5 years or after resale.
5	5	476	II.A.1.d	Government requires utilities to help pay for weatherizing households.
6	6	471	II.A.1.c	Government requires industry to help pay for weatherizing households.
7	7	469	I.A.1.b	Government requires replacement of existing stoves with certified low-emitting units.
8	15	424	I.A.2	Government required rating of burning units for emissions, to allow sale.
9	16	422	III.A.4.a	Government requires commercial wood sales to include information on moisture content levels.
10	17	418 385	III.A.1.a III.A.a.b,c,d	Chimney sweeps test household emissions.
11	18	416	II.A.2.b.3	Reduce/eliminate fall firewood cutting on federal lands to increase chance of proper drying.

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[1] From Table C1, Appendix C

[2] From Table B1, Appendix B

TABLE 3 (Cont.)

Entry	Overall[1] Rank	Overall[1] Score	I.D. No.[2]	Description of RWC Control Strategy
12	19	415	II.A.4.b	Allow new burning unit only if certain efficiency standards met.
13	20	407	II.A.4.a	Allow new burning unit only if it provides a substantial net heat gain.
14	32	360 342	II.A.3.a II.A.2.b.2	Emission Density Zoning - allow only X wood burners per $(\text{mile})^2$ based on pollutant dispersion capacity.
15	35	359 347	II.A.2.b.1 II.A.2.b.2	Firewood cutting on federal lands limited based on air quality levels.
16	48	273	II.A.2	RWC cutbacks during air pollution episodes.
17	51	252	II.A.2.a	Require USFS/BLM EIS to assess air quality effects of their firewood releases.

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[1] From Table C1, Appendix C

[2] From Table B1, Appendix B

TABLE 4
Ranking of RWC Control Strategy Elements
vs
WANT Criteria - Market Incentives/Disincentives

Entry	Overall[1]			Description of RWC Control Strategy
	Rank	Score	I.D. No.[2]	
1	10	459	I.B.1.a.4	Consumer subsidy to buy cleaner burning combustion equipment.
	11	453	I.B.1.a.3	
2	12	447	I.B.1.c	Government sponsored $50,000 prize to designer of first burning unit to cost $\leq \$1000$ and emit ≤ 1 g/kg..
3	14	436	I.B.1.b	Tax disadvantage to companies proportional to the emissions levels of their burning units.
4	21	404	II.B.1.b	Government subsidizes weatherization in all areas.
5	23	401	I.B.1.a.1	Government subsidizes purchase of cleaner new burning unit.
		392	I.B.1.a.2	
6	26	394	II.B.4.b	Lower residential rates for gas/oil.
		394	II.B.4.c	
7	30	363	II.B.4	"Lifeline" electricity rates.
8	38	345	I.B.1.b.2.b	Government subsidy to manufacturers of burning units for pollution measuring equipment.
		326	I.B.1.b.1.a	
9	42	310	III.B	Government subsidizes regional wood drying facility.
10	43	304	II.B.1.a	Government subsidizes weatherization only in areas with severe pollution potential.
11	47	283	II.B.2.a	Increase wood prices to decrease RWC by greater residue utilization
		271	II.B.2.b	Increase wood prices by raising cutting fees.
12	49	273	II.B.4.d	Subsidize solar energy as RWC alternative.
13	53	234	II.B.3.b	Increase RWC cost by encouraging fire insurance increases or property tax increases for RWC users.
		225	II.B.3.a	

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[1] From Table C1, Appendix C

[2] From Table B1, Appendix B

TABLE 5

Ranking of RWC Control Strategy Elements
vs
WANT Criteria - Public Information/Technology Transfer

Entry	Overall[1] Rank	Overall[1] Score	I.D. No.[2]	Description of RWC Control Strategy
1	8	468	III.C.3.a	Government distributes information on proper stove sizing.
2	9	465	III.C.3.b	Trade Association develops rating program for how much space can be heated by a given unit (sizing).
3	13	437	I.C.2.b I.C.2.c	Mandatory emissions testing of burning units by Trade Association.
4	22	403	II.C.2	Make public aware of true wood heating costs.
5	24	395	I.C.1.a	Government provides free fully-staffed emissions testing facility.
6	25	396 387 380	II.C.1.c II.C.1.a II.C.1.b	Disseminate information on burning unit efficiency by neutral organization, government, or trade association.
7	27	383 390	III.C.1.b III.C.1.a	Educate wood users as to moisture content effects on emissions and efficiency.
8	28	364	I.C.3.a	Government sponsors $50,000 prize for first test procedure system costing less than $100/test.
9	29	364 358	I.C.3.a I.C.3.b	Publish information on burning unit design considerations/research ... government or trade association.
10	31	360	I.C.2.a	Voluntary Trade Association emissions rating program.
11	33	359	I.C.1.b	Government tax credits on equipment or service for emissions testing of burning units.

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[1] From Table C1, Appendix C

[2] From Table B1, Appendix B

TABLE 5 (Cont.)

Entry	Overall[1]			Description of RWC Control Strategy
	Rank	Score	I.D. No.[2]	
12	34	357	I.C.1.c	Government funds development of standardized, simpler, cheaper emissions test procedures for RWC units.
13	39	341 331	III.C.2.a,d,e III.C.2.b,c	Distribute information on avoiding creosote buildup/minimizing emissions ... by government or trade association.
14	40	335	II.C.4	Make public aware of frequency of fires associated with RWC, to discourage use.
15	41	315	III.C.1.d	Distribute free moisture meters to commercial wood distributors.
16	44	298	II.C.3	Make public aware of health concerns related to indoor air pollution from RWC.
17	45	293	II.C.6.a	Promote personal insulation - wearing warmer clothes indoors to reduce heating needs.
18	46	285 283 275	II.C.5.a II.C.5.c II.C.5.b	Promote alternative radiant heat sources - e.g., natural gas fireplaces, passive solar, gas heaters.
19	50	264	II.C.6.b	Promote personal insulation - spot heating of key areas in house.
20	52	235	III.C.4	Concerned neighbor approach - neighbors tell others how to reduce RWC emissions.
21	54	211	II.C.2	Suggest households limit annual fireplace usage to 10 occasions to reduce heat loss.

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[1] From Table C1, Appendix C

[2] From Table B1, Appendix B.

respectively. This allows these three major methods of achieving RWC controls to be considered separately. However, the "overall rank", among all seventy-five strategy elements, also is shown in column two of each table. Note that for simplicity, when similar strategy elements ranked close together, they were combined in the final list (in Appendix B). Thus, this final list contains 54 ranks into which the 75 strategy elements were grouped.

It is important to keep in mind that the numerical scores and resulting rankings are merely a device to aid in evaluating a large group of possible strategy elements. The absolute scores are less important than the relative ranking of strategy elements. It also is important to remember that the ranking represents the relative degree to which all WANT criteria are satisfied, simultaneously, by a given strategy element.

Top ranking strategy elements are not necessarily those deemed most able to reduce RWC emissions, although they likely scored well on this criteria. Top ranked strategy elements represent the best overall rating, taking into account not only emissions control, but also other key attributes such as wide applicability, public acceptance, consumer cost, administrative feasibility, etc..

The degree of subjectivity inherent in this evaluation process also should be recognized. It can strongly reflect the views and bias of the analyst, however unintended. The assignment of scores for satisfying WANT criteria, and even the relative weighting of WANT criteria, involves personal judgements by the analyst. No two analysts attempting this task would produce identical results, and some might produce widely varying results. Nevertheless, this Keppner-Tregoe process provides a systematic (if laborious) way to evaluate a large number of possible choices against a list of weighted decision criteria to achieve a relative ranking of the choices. The results can be analyzed as to why certain choices ranked higher and others low. This is done in subsection B2 below for the strategy elements shown in Tables 3, 4, and 5. Prior to that, however, key considerations in assigning WANT criteria satisfaction scores are discussed in subsection 1, below.

1. Assigning WANT Criteria Scores

The judgements made in the assignment of scores for satisfaction of WANT criteria has an obvious and direct influence on the eventual ranking of control strategy elements. To undertake this scoring effort systematically, and to assure consistency among scores, required establishing at least a rough decision framework for scoring for each WANT criteria. This decision framework, and judgements and assumptions used in scoring, can build biases into the scoring process which help determine and explain the resulting ranking of control strategies. Care must be taken to minimize such bias.

To help systematize scoring the following general decision framework was used for each WANT criteria:

Each control strategy element was to be assigned a score from 1-10 based on the degree to which it satisfied a given WANT criteria. For each WANT criteria, five satisfaction levels were described as illustrated in Table 6 for WANT criteria #4 (maximize public acceptance). Each represented a scoring range of several possible total points.

All RWC control strategy elements were assigned to one of the satisfaction levels, and assigned a score within its range of possible points. To further assure consistency in scoring a preliminary identification of the highest and lowest scoring strategy elements was made, so that scores for the rest would fall in appropriate intermediate ranges. Also, similar strategy elements were assigned similar scores.

Appendix B (Table B2) contains the scores assigned to each strategy element, for each WANT criteria, and which resulted in the rankings in Tables 3, 4, and 5.

TABLE 6

General Satisfaction Levels for WANT Criteria #4 - "Maximum Public Acceptance"

Satisfaction Level	Possible Points	Criteria for satisfying to this level
Fully	9-10	Fully acceptable; some significant support; no significant oppositon.
Well	7-8	Acceptable to most parties; some support; no significant opposition.
Moderately	5-6	Lukewarm acceptance; most people don't know or care; or, offsetting support and opposition.
Poorly	3-4	Acceptable primarily to environmentalists; average person wary or opposes.
None	0-2	Not acceptable to many; strong opposition.

2. Discussion of Resulting Ranking of Control Strategy Elements

Comparison of Tables 3, 4, and 5 indicates that regulatory actions tended to rank higher than market incentives/disincentives and both tended to rank higher than public information/technology transfer approaches, as RWC control measures. Analysis of individual scores (Appendix B, Table B2) indicates this is due to a tendency for regulatory approaches to score higher in the more heavily weighted WANT criteria, e.g., reducing household RWC emissions (#1), wide applicability (#3), discouraging worst appliances (#5). Similarly public information/technology transfer approaches tended to score low in these areas.

This also makes common sense, in that the success of a control strategy element often seems more assured under regulatory pressures than under reliance upon voluntary actions, or based on public information about the strategy. There is less choice under regulatory approaches. People tend to obey the law, even if they dislike it. Regulatory approaches also depend less on an informed public. Regulations seek out affected parties and regulate some aspect of their actions. The success of approaches based on incentives or public information depend first on whether affected parties even know about them, and second on whether they choose to act in the manner intended by the strategy.

Looking at the three tables individually, the following strategy approaches received consistently higher scores:

- Proper sizing of wood burning units (A, C)
- Emissions testing and certification of wood burning units
- Weatherization of homes
- Regulatory efforts or subsidies to encourage development and use of cleaner burning units
- Wood moisture content controls

The following types of approaches received consistently lower rankings:

- Limit RWC, by restricting
  - wood supply
  - burning in air quality problem areas (even during episodes, surprisingly)
- Limiting RWC by increasing costs of
  - firewood
  - fire insurance for RWC homes
- Promoting alternative heating sources, such as solar, or radiant gas heaters
- Promoting personal actions, such as dressing more warmly at home, voluntarily limiting RWC, or advising neighbors how to burn more cleanly

Many of the higher scoring control strategy elements were incorporated into one or more of the final RWC control strategies evaluated in Section V.

V. GENERIC APPROACHES TO REDUCING RWC EMISSIONS - QUANTITATIVE ESTIMATES OF EMISSION REDUCTIONS ACHIEVABLE

This section discusses the following generic strategy approaches to reducing RWC particulate emissions:

A. Improving Burning Unit Design
  1. Improved design of new stoves
    a. Testing of wood stoves/furnaces, and certification of compliance with an established emission limit, as a prerequisite for allowed sales
    b. Testing/certification as a prerequisite of stove/furnace sales, plus a financial incentive (33% tax credit) to buy the cleaner (certified) stoves
    c. Testing/certification as a basis for mandatory labelling of all stoves/furnaces sold, which specifies their efficiency and emissions performance
    d. Testing/certification as a basis for mandatory labelling, plus the 33% tax credit for clean units
  2. Modification of installed stoves/furnaces, including:
    a. Air inlet modifications
    b. Insertion of firebrick in stove box
    c. Fans to improve heat transfer
    d. Add-on particulate control devices:
      1. Steel wool mesh filter
      2. Catalytic afterburner
  3. Improved design or add-on devices for fireplaces
    a. Underfire air
    b. Electrostatic precipitator
    c. Glass doors

B. Reducing Wood Usage
  1. Reducing home heating requirements
    a. Weatherization
    b. Reducing stove charge size
  2. Improving wood fuel quality
    a. Selection of wood with higher heating value
    b. Moisture control (seasoning)

        3. Direct restrictions of wood usage
            a. Episode controls
            b. Emission density zoning
    C. Improving RWC Operating Practices
        1. Initial selection of burning units - sizing
        2. Operating technique modifications
            a. Discouraging airtight stove operation
            b. Charging larger pieces of wood
        3. Periodic inspection of RWC equipment

This section also estimates the potential ability of these strategy approaches to reduce RWC emissions (primarily particulate emissions, including volatile organics). These quantitative estimates of emissions reduction potential are summarized in Table 7 and documented in more detail in Appendix D. These estimates are largely speculative, because little exists in the way of quantified experience in controlling RWC as a pollution source. For example, there is still much to learn about how to control the combustion process within stoves and fireplaces to burn most efficiently and cleanly (emissions).

The approaches discussed here for reducing RWC air pollution also could be implemented using a variety of means, which could be summarized in the following categories:

1. Regulatory actions or requirements
2. Subsidies or market incentives
3. Information distribution or technology transfer

The many possible combinations of strategy approaches and implementation means are too numerous to examine individually regarding their potential for reducing RWC emissions. (Section IV examines and ranks a large number of such individual strategy elements using selected criteria.) However, examples of all three categories of implementation methods are included in the strategy approaches analyzed in this section, as well as in the final strategies evaluated in Section VI of this report.

TABLE 7
Comparison of Estimated Particulate Emission Reductions
Achievable by Generic RWC Control Strategy Approaches

Generic RWC Emissions Control Strategy Approach	Potential Particulate Emissions Reductions (%)				
A. Improving Burning Unit Design	A. Improving Burning Unit Design				
		YEAR			
		1985	1990	1995	2000
1. Promotion of design and use of cleaner new stoves/furnaces					
a. Testing/certification as prerequisite to sales or installation.	1a.	2	8	22	30
b. Test/certification as prerequisite to sales, plus $400 (33%) tax credit.	1b.	3	11	30	39
c. Testing/certification as basis for mandatory labeling prior to sales,specifying efficiency and emissions performance.	1c.	1	3	8	11
d. Testing/certification/labeling, plus $400 (33%) tax credit.	1d.	1	5	15	21
		(Table D3 values X .7)			
2. Modifications of installed stoves					
a. Air inlet modifications.	2a. No basis for emission reduction credits.				
b. Insertion of firebrick in stove box.	2b. No basis for emission reduction credits.				
c. Heat transfer improvement (fans).	2c. Negligible (0-1%)				
d, Add-on Particulate control devices	2d. Negligible (0-1%)				
3. Improved design or add-on devices for fireplaces					
a. Underfire air.	3a. 1% by 1990; 2% by 2000.				
b. Electrostatic precipitator.	3b. 46% (single test); expensive ($1,400).				
c. Glass doors.	3c. No basis for emission reduction credits.				

TABLE 7 (Cont.)

Generic RWC Emissions Control Strategy Approach	Potential Particulate Emissions Reductions (%)
B. Reducing Wood Usage	B. Reducing Wood Usage
1. Reducing home heating requirements - Weatherization	
a. All households.	1a. For 1990 3.5%; for 1995 7.0%.
b. Households installing new wood stove/furnace.	1b. For 1990 2.5%; for 1995 5.0%.
2. Improving wood fuel quality	
a. Select fuel with higher heating value.	2a. No basis for emissions reduction credit.
b. Moisture control.	2b. 6.2%
3. Direct restrictions on wood usage	
a. Episode controls.	3a. 33% per episode day.
b. Emission Density Zoning.	3b. No basis for emissions reduction credit.
C. Improving RWC Operating Practices	C. Improving RWC Operating Practices
1. Initial selection of burning unit	
a. Sizing.	1a. 7% by 1990; 10.5% by 2000.
2. Operating techniques	
a. Discouraging airtight operation.	2a. No basis for emissions reduction credit.
b. Charging larger pieces of wood.	2b. 11.5%.
3. Inspection of RWC households.	3. No basis for emissions reduction credit.

Thus, this section describes what we believe are the primary generic approaches to controlling pollution from RWC, and attempts to quantify where possible their potential for reducing average RWC emissions levels. These quantitative estimates or assumptions are used in Section VI of this report as a primary basis for scoring and ranking alternative strategies based on their relative RWC emissions reduction potential. For example, these quantitative estimates will be the primary basis for scoring strategies vs WANT criteria #1 and #2 in the Keppner-Tregoe evaluation of final strategies, in Section VI of this report.

A. IMPROVING BURNING UNIT DESIGN

1. Improved Design of New Stoves

An assessment of several stoves of advanced design suggests that affordable stoves with particulate emission rates less than 5 g/kg should be available, which is 25% of the average emission rate (20 g/kg) assumed in this study for the current mix of existing wood stoves (see Appendix D, Section A1 for details). If an affordable stove with emissions as low as these advanced designs can be developed in the near future, it could provide the most effective approach to reducing RWC emissions of all approaches examined in this study. This assertion is verified by the higher RWC emissions reduction potential estimated for the following four strategy approaches, than for any other approaches examined in the report (see Table 7).

a. Testing/Certification as Prerequisite for Sales

Under this strategy approach new stoves or furnaces could not be sold if they did not comply with established emission limits. A standardized testing and certification program, probably government operated, would be needed to provide objective and consistent evaluation of burning units.

Medford, Oregon[11] and Missoula, Montana[10] have advocated setting wood stove emission limits at 5 g/kg in the near future, but neither provided for testing/certification.

Enforcement through building permit or other permit processes is a likely proposal. However, building permits can be easily circumvented in many communities. A new permit process for RWC devices probably would be very unpopular, and possibly illegal in some states, e.g., Oregon law prohibits regulation of air emissions from residential space heating.[12] If this strategy approach were applied only to air quality problem areas within a region, cheaper, "dirtier" stoves probably would continue to be locally available for sales in competition with the cleaner units. For purposes of this analysis, it was assumed that, under mandatory testing/certification, only 60% of the new stoves purchased would be certified - either because of circumvention of the requirement, or because it might be applied only to limited geographic areas with air quality standard violations.

b. Testing/Certification as Prerequisite for Sales, Plus Tax Credit for Purchase of Certified Unit

This approach would combine the testing/certification program described above with a financial incentive to purchase the cleaner (certified) units, in the form of a tax credit. A $400 tax credit, or 33% of the assumed $1200 price (1984), was selected for this analysis based on considerations explained in Appendix D. It was assumed that this combined strategy approach of testing/certification plus tax credit could be 90% effective for purposes of analysis of potential emissions reductions. That is, 90% of the new and replacement stoves purchased would be the cleaner (certified) units. This strategy approach was the most effective at reducing stove/furnace emissions of any examined in this report - achieving a 11% reduction by 1990 and 39% by 2000 (Table 7).

c. Testing/Certification as Basis for Mandatory Labeling Which Specifies Efficiency and Emissions

In this approach the thrust of testing and certification would be to require labeling of all stoves or furnaces offered for sale, which specifies their overall efficiency and emissions performance, as established by the testing. This information also could be published in other ways, to better inform consumers, in hopes that they will exercise a preference for cleaner, more efficient units.

Shelton estimated that most stoves operate at about 40% to 60% overall efficiency in the Woodburner's Encyclopedia, published in 1979.[13] Some of the stoves and furnaces now emerging in the market place have overall efficiencies in excess of 75%, which means they can provide equivalent heat output while using only about two-thirds as much wood (.50/.75). Since part of the manner by which these units achieve higher efficiencies is by higher combustion efficiency, a labelling program which encourages people to buy the most efficient units will tend to encourage them to purchase lower-polluting units. This is the primary mechanism by which a labelling program could lead to lower emitting units.

A secondary mechanism which could result in cleaner units being purchased is the concern by some individuals about air pollution. Some small fraction of households purchasing cleaner stoves would purchase low-emitting units in order to assist in "protecting the environment".

This approach was assumed likely to be no more than 20% effective, i.e., 20% of new stove/furnaces would be the cleaner certified units - in part because of the likely availability of cheaper "dirtier" units, and the high influence of purchase price on consumer choices.

d. Testing/Certification/Labelling Plus Tax Credit

This approach is the same as the one just described, but with availability of the $400 or (33%) tax credit described for approach 2 above.

Analysis of these four strategies for promoting development and installation of much cleaner burning stoves required a basic assumption about the probable availability of the cleaner units commercially. The following assumption was made for purposes of this analysis, based on review of costs and performance of existing advanced design stoves, as described in Appendix D, Section A .

ASSUMPTION: Wood burning stoves will be available by January 1984 at a cost of $1200 or less, with particulate emission rate of 5 g/kg or less - i.e., 75% less than the current estimated average emission rate of 20 g/kg.

It also was necessary to postulate a level of wood fuel use which would be altered by the implementation of any strategy approach, and how effective each strategy approach might be. Assumptions about strategy effectiveness are stated above. The BASE CASE long-term trend (1970-2000) projections of wood stove fuel use for Portland, Oregon generated in Task 3 of this study, were used as the baseline wood fuel use rate. Appendix D describes the assumptions used to calculate the RWC particulate emissions reductions shown in Table 7 for these four strategy approaches.

2. Modifications of Installed Stoves/Furnaces

a. Air Inlet Modification

Barnett has reported a 50% reduction in particulate emissions from a stove in which a simple modification introduced inlet air between the logs near the center of the stove.[1i] However, neither manufacturers nor homeowners seem likely to pursue this "add-on" approach to any great extent, due to many factors, including 1) lack of standardized inexpensive emissions test procedures needed to keep research and development costs down; 2) difficulty in developing inexpensive modification kits which could be applied to existing stoves; and 3) difficulty and potential safety problems of "do-it-yourself" modification.

These authors could find no basis for assigning any emissions reduction credit to this approach.

b. Insertion of Firebrick in Stove box

Lining firebox walls with refractory or firebrick can theoretically help keep combustion temperatures high enough for good combustion efficiency - e.g., ignition of volatilized wood gases requires 670°F.[13] However, Barnett's research on a thin-walled stove did not show significant emissions reduction when a firebrick lining was added to that stove.[11] Accordingly, these authors assign no emissions reduction credit to this approach.

c. Heat Transfer Improvement (Fans)

Theoretically, heat transfer efficiency could be improved by using a fan or blower to transfer more heat into a room that would otherwise escape through the stove stack. If this improved thermal efficiency could be achieved without reducing combustion efficiency, less wood would need to be burned to provide equivalent space heating, and emissions should drop proportionately.

Research by Shelton[14] and Barnett[15] suggest that increases in efficiency through forced air heat exchange would not exceed 5-10%. This would require 10-20% of homeowners to install fans or blowers, in order to achieve even a 1% reduction in emissions. This is not considered likely, so this approach is assigned a negligible (0-1%) emission credit.

d. Add-on Particulate Control Devices

Only this study (Task 5) and one other by the Oregon Department of Environmental Quality[1j] have reported emissions test results for add-on devices to control particulate emissions from wood stoves. The two devices tested -- a steel wool mesh filter and a catalytic afterburner -- were inserted in the stack, immediately above the firebox. In very limited testing 1) the catalytic afterburner afforded 10% less emissions, which is within experimental error, and; 2) the steel wool mesh filter reduced particulate emissions by 60% in one pair of tests when tested at a high burn rate. In a second set of tests (2 runs) conducted in a different test facility by a different researcher, use of the device resulted in essentially no emission reduction.

Shelton also tested both these units for their potential to reduce creosote deposition in the exhaust stack.[16] Creosote deposition is less than a perfect indicator of particulate emissions because stack temperature differences can yield greater or lesser creosote deposition in the stack without yielding a corresponding change in particulate emissions. In that testing, creosote deposition was reduced by 23% by the mesh filter device and by 45% by the catalytic afterburner. Shelton did note some clogging problems with the mesh filter device.

The cost of these devices ($100-350), questions about long term effectiveness, and the inevitable strong public opposition to any regulatory requirement for their use, makes it highly unlikely that this strategy approach could contribute significantly to RWC emissions reductions in the next 10 years, (except perhaps as a design feature in new stoves). Accordingly, their emissions reduction potential as a retrofit approach is judged to be negligible (0-1%), based on the limited available data.

3. Improved Design or Add-on Devices for Fireplaces

Because fireplace combustion is open combustion, it is more difficult to optimize air/fuel ratios, and residence time for combustibles in a sufficiently hot combustion zone.

a. Underfire Air

Based on a single, limited set of tests by PEDCo, Inc. a 20% emissions reduction appears possible by introducing air under the combustion zone of the fireplace during burning. At a cost of $100 or less for such a fireplace modification, this approach warrants more research - especially at more "normal" burn rates than were used by PEDCo. However, overall RWC emissions (stoves/fireplaces) would be reduced only an estimated 1% by 1990 and 2% by 2000 with this approach.

b. Electrostatic Precipitator

The limited PEDCo tests also included a single test of a commercially available electrostatic precipitator ("Smog-Hog").[17] A substantial emissions reduction (46%) was achieved. However, the cost of this unit today ($1400) effectively eliminates serious consideration of it for households. Accordingly, it was not assigned emissions reduction credits.

c. Glass Doors

Glass doors shut during the burndown/smoldering phase of a fire can reduce household heat loss. During active burning, a closed glass door inhibits space heat transfer, lowering overall efficiency. However, there is no evidence that glass doors either increase or decrease combustion efficiency, which affects emissions. Accordingly, no emissions reduction credits are assigned.

B. REDUCING WOOD USAGE

Three types of strategy approaches were considered in this section for reducing wood usage: (a) reducing home heating requirements, e.g., through weatherization; (b) improving fuel quality, e.g., through moisture control (seasoning), or selection of wood fuel with higher heat content, and ; (c) direct restrictions on wood usage, e.g., through regulatory actions such as limited bans on RWC during air pollution episodes (episode controls), or more general restrictions on RWC in air quality problem areas, such as emission density zoning.

1. Reducing Home Heating Requirements - Weatherization

In this study, weatherization was assumed to reduce home heating requirements by 30-50%, or an average of 40%[5]. Since most RWC households also rely to some extent upon some conventional heating fuel (oil, gas, electricity), they could respond by reducing reliance upon these conventional fuels, or wood, or both. The estimated range of emissions reduction derived here (7 to 16%) for weatherization of all RWC households, depends on the assumptions used. Two different scenarios (using different assumptions) were evaluated to determine a range of particulate emissions reductions that could occur. The actual emissions reductions will vary from area to area and will depend on the percentage of homes actually weatherizing and the changes in stove operation that occur after weatherization.

Case #1

Scenario Assumptions:

- Household heating requirements = 50 million Btu/yr, with 20 million Btu from conventional fuel and 30 million from wood.
- Weatherization results in reduced reliance on both fuels by 10 million Btu/yr (33% reduction for wood, 40% overall); and 15% less burn days/year (on marginally cool days).
- 33% of wood stove owning and weatherized households could be "educated" to reduce their reliance on wood by reducing charge

size (this would allow them to maintain their accustomed charge interval, but a smaller fire). The remaining 67% will use the same size of charge as before weatherization, but will reduce the burn rate by re-charging less frequently.

- Woodstove owners living in weatherized houses will replace their oversized stoves with other oversized stoves.
- 60% of Oregon's RWC households need weatherization; 80% of these could be induced to weatherize.

Results:

- 48% of RWC households will weatherize (60% x 80%).
- There will be a 7.2% reduction in emissions from all woodstove owning households based on no burning during 15% of days (15% x .48 = 7.2%).

For those 67% weatherized woodstove owning households that choose not to reduce wood charge size, total emissions on burn days will be the same as before weatherization. The reduced wood usage is exactly offset by the higher emission rate (g particulate/kg wood burned) caused by the reduced burn rate[1]. That is, the emission rate rises proportionally as the burn rate falls.

For those 33% weatherized woodstove owning households that do reduce the wood charge size on burn days, the percent reduction in daily emissions equals the percent reduction in heating requirements.

$$\left(\frac{\text{33\% total wood reduction - 15\% total wood reduction because of no burn days}}{\text{1 - 15\% no burn days}} = 21\% \right)$$

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[1] Butcher's equation: emission rate (g/kg) = constant (g/kg-hr) x $\left(\frac{\text{wood charge size (kg)}}{\text{burn rate (kg/hour)}}\right)$

That is, the 21% heating reduction equals 21% wood use reduction which equals the 21% of emissions reduction on burn days, for those households owning wood stoves, weatherizing, and reducing wood charge size. This equals a 2.9% emissions reduction for all woodstove households (21% x .85 x .48 x .33 = 2.9%).

- The resulting emissions reduction of 10.1% (2.9% + 7.2%) is for woodstoves only. The overall emissions reduction for all RWC households including fireplaces is 7.1% (10.1% x .70).

Case #2

Scenario Assumptions:

- As above, 48% of RWC households will weatherize.
- Weatherization results in 40% less fuel required per day, with equal percent reductions for wood and conventional fuels. Fifteen percent of days are marginally cold where wood is no longer burned after weahterization.
- 100% of owners of weatherized homes will either reduce the wood charge size proportionally to reducing the burn rate, or will burn at the same burn rate but burn fewer hours per day after weatherization.
- Oversized units will be replaced (in the 10-15 year replacement time period) with smaller units after weatherization occurs.

Results

- There will be a 7.2% overall reduction in emissions from woodstoves based on no burning during 15% of days (15% x .48 = 7.2%).
- There will be a 16.3% overall reduction in emissions from woodstoves based on reduced burning on burn days (85% x .48 x .40 = 16.3%).
- The emission reduction for all RWC households (woodstoves and fireplaces) is 16.4% ((7.2% + 16.3%) x .7 = 16.4%).

2. Improving Wood Fuel Quality

a. Selection of Wood with Higher Heating Value

The intrinsic heating value of wood (Btu/air-dried cord) can vary by a factor of 2 among different wood species (Appendix D). While this offers some potential for reducing RWC emissions, two factors make this impossible to quantitatively estimate, and probably negligible. First, there is no information available on particulate emissions by species. Thus higher heat value may or may not correspond to higher emissions characteristics. Second, while the more common wood species available in the Pacific Northwest - e.g., Douglas fir, Ponderosa pine - have low to medium heating values, supplies of wood with higher heating values are limited. Thus, people would be unable to switch in mass to wood of higher heating value. Accordingly, this strategy approach was assumed to have negligible emissions reduction potential.

b. Moisture Content Control (Seasoning)

The next two sections describe estimates for potential reductions in RWC particulate emissions from fireplaces and stoves which could be achieved by reductions in firewood moisture content.

(1) Potential Fireplace Emissions Reductions

For fireplaces, decreases in wood moisture content levels result in lower particulate emission factors. This is because more complete combustion occurs with lower moisture content woods. Although particulate emission tests for fireplaces are not available for a variety of wood moisture contents, measurements of combustion efficiency for fireplaces with different wood moisture content levels are available from Shelton[1k]

(Figure 3). In this analysis the quantity (1.0 - combustion efficiency) is used to indicate relative particulate emissions at different moisture contents in Figure 3.

Focusing on the portion of the curve between 18% m.c. and 25% m.c., it appears that each 1% decrease in wood moisture content yields a 1.6% decrease in emissions. However given the "flattening out" of the curve near 25% m.c. and the fact that most wood burned in the Pacific Northwest[19], is thought to have a moisture content level in excess of 25%, these authors estimate each 1% decrease in wood moisture content results in a .8% decrease in particulate emissions for fireplaces. These assumptions are discussed in more detail in Appendix D, Section B2b(1).

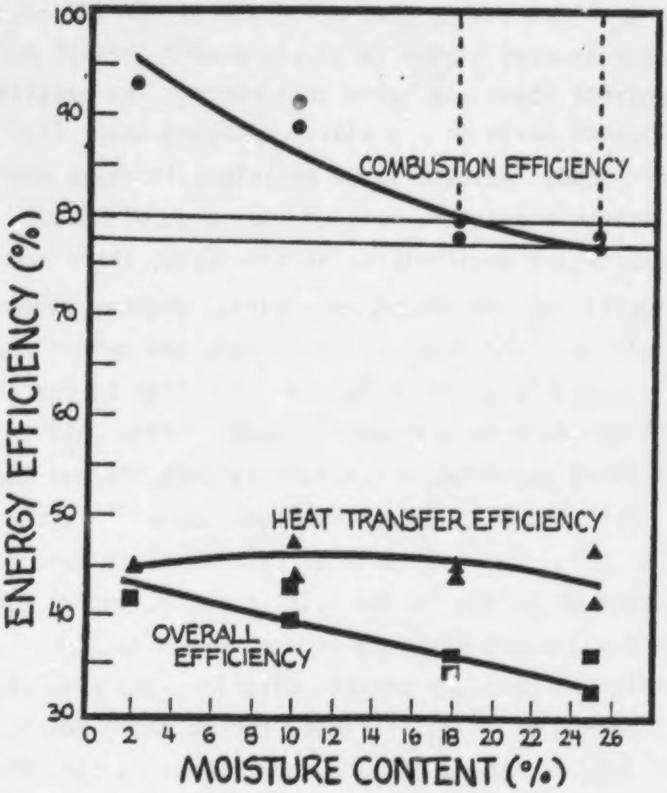
In order to derive an estimate of how much fireplace emissions could be decreased by educational programs which advocate the use of drier wood, some estimate must be derived for how much moisture content could be reduced. Based on several estimation techniques discussed in Appendix D, these authors estimate that the average moisture content of wood burned in fireplaces could be decreased by about 2% which would yield a 1.6% reduction in particulate emissions from fireplace burning (2% x 0.8 = 1.6%). For an area where fireplaces account for 30% of the total RWC emissions, a reduction of 0.5% in total RWC emissions is derived (1.6% x .30 = .48%).

(2) Potential Stove Emission Reductions

For stoves, even though some particulate measurements vs moisture content have been reported by several researchers (Rudling et.al.[11], Del Green Associates, Inc.[20], and Barnett[11]), the most useful data is available again from Shelton in the form of combustion efficiency

FIGURE 3

Effect of Wood Moisture
on
Fireplace Combustion Efficiency



The dependence of efficiencies on moisture content in an open fireplace. Here power output could not be held constant but increased with decreasing moisture content. Fuel loads were of uniform size and were added when the previous load had been reduced to charcoal.

Source: Shelton [1k]

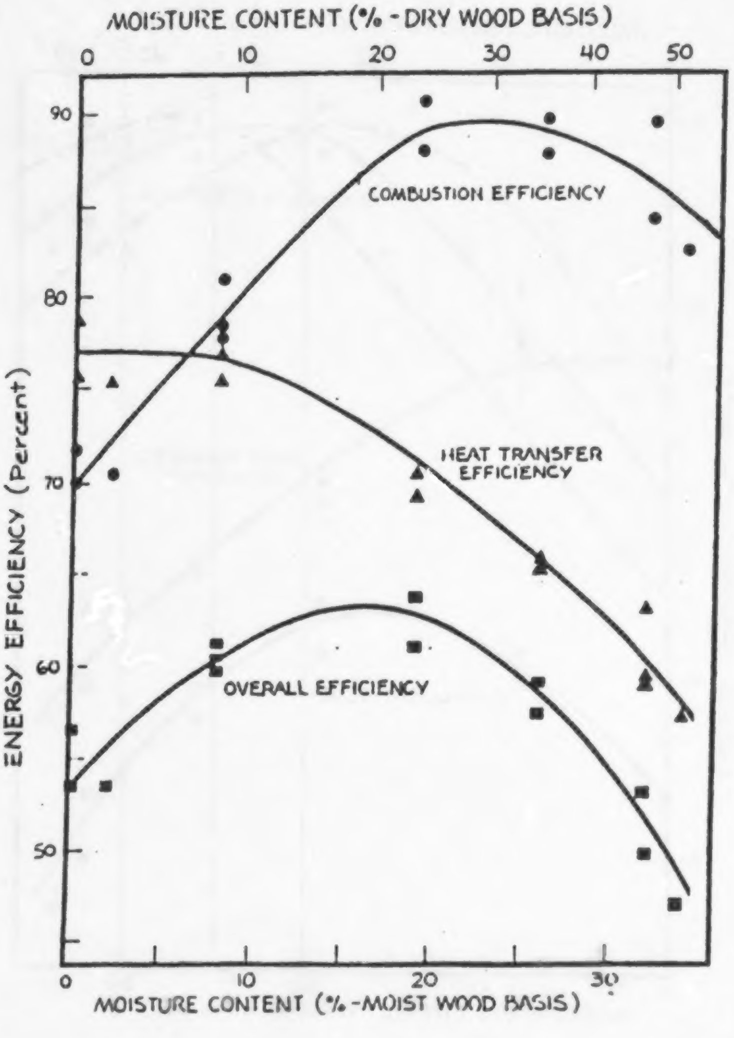
vs wood moisture content[1k] (Figure 4). We assume again that particulate emissions are proportional to the quantity (1.0 - combustion efficiency).

Based on Shelton's testing on one stove, it appears that optimum wood moisture content lies between about 20 to 25% (wet basis) with worse combustion efficiency and hence assumed higher particulate emissions at moisture contents above and below this range. The results of six emission tests on one stove conducted under Task 5 of this study indicate stove emissions increase when wood moisture content is outside the range of 20-30%, wet basis. Despite the availability of this data, there are still significant uncertainties - first, whether other stoves would have the same optimum range, and second what sort of a wood moisture content distribution is characteristic for the Pacific Northwest. Lacking firm data on either of these subjects, a sensitivity analysis was conducted to estimate what emission reductions would occur 1) for Shelton's original curve vs results if it were shifted either 5% points to the left or right, and 2) for two different assumed moisture content distributions. The two different moisture content distributions evaluated were: 1) one-third of all firewood burned has a moisture content of 25%, one-third has 30%, and one-third has 35%, and; 2) three-eighths has a moisture content level of 25%, one-half has 30%, and one-eighth has 35%. Differences in emissions when these moisture contents are reduced were calculated based on the quantity (1.0 - combustion efficiency), and the three different curves shown in Figure 5 as explained in Appendix D, Section B2b(2).

Table 8 shows the results for these six different cases, which are explained in Appendix D in detail. The

FIGURE 4

Effect of Wood Moisture Content
on
Stove/Furnace Combustion Efficiency

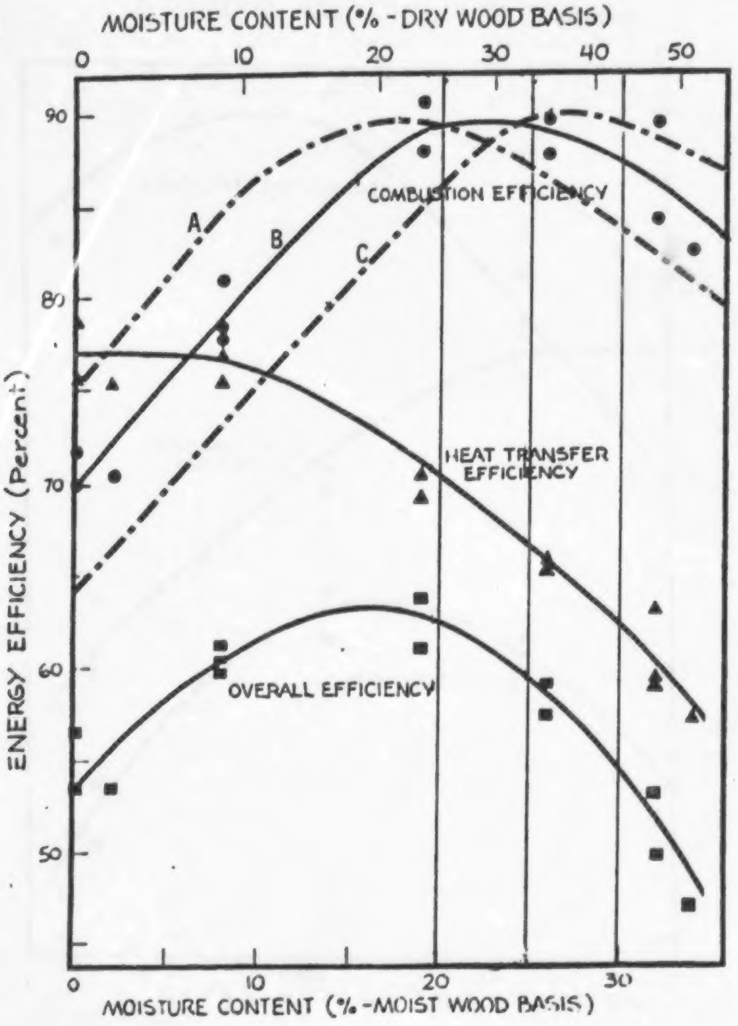


The dependence of efficiencies on fuel moisture content in an airtight stove. The air inlet setting was varied to maintain an average power output of about 17,000 Btu per hour for all moisture contents. The fuel load volume was approximately constant.

Source: Shelton[1k]

FIGURE 5

Three Assumed Moisture Contents
vs
Combustion Efficiency Curves for Stoves/Furnaces



The dependence of efficiencies on fuel moisture content in an airtight stove. The air inlet setting was varied to maintain an average power output of about 17,000 Btu per hour for all moisture contents. The fuel load volume was approximately constant.

Source: Adapted from Shelton[1k]

TABLE 8

RWC Emissions Resulting from Six Hypothetical Cases of Wood Moisture Content Control

Curve Evaluated in Figure 5	Assumed Percentage of Wood With Moisture Content of 25/30/35%	Resultant Emission Reduction for Wood Burned in Stoves*
C (Rightmost)	33.3/33.3/33.3	5.5%
C	37.5/50.0/12.5	3.5%
B (Center)	33.3/33.3/33.3	10.5%
B	37.5/50.0/12.5	8.1%
A (Leftmost)	33.3/33.3/33.3	11.7%
A	37.5/50.0/12.5	9.9%
	Average	8.2%

* Assuming a wood moisture content reduction of 2%.

results range from about a 3% to a 12% emission reduction. As a best estimate, we assume that the arithmetic average would apply. That is, that a vigorous educational program which reduces average wood moisture by 2% could yield about a 8.2% reduction in particulate emissions from residential wood burning in stoves. Assuming stoves will account for about 70% of all RWC emissions by 1983 based on Task 3 projections, total RWC emissions from stoves are estimated to be reducible by 5.7% (8.2% x .70 = 5.7%) by focusing on stoves alone.

Combining the emissions reductions estimated for fireplaces (0.5%) and stoves (5.7%) yields 6.2% as the estimated reduction in total RWC particulate emissions achievable through programs which produce the assumed 2% overall average reductions in firewood moisture content. Depending upon the amount of green wood (% moisture greater than 40%) currently being burned, significantly higher emissions reductions could be achieved through programs which educate owners regarding proper wood seasoning.

3. Direct Restrictions on Wood Usage

Two strategy approaches were evaluated which were based on reducing the amount of wood fuel used in order to reduce RWC particulate emissions. Episode controls focus on reducing wood usage on the most severe pollution days only. Emissions density zoning would attempt to restrict the average level of wood burning in designated air quality problem areas.

a. Episode Controls

The strategy of mandating or requesting a reduction in wood burning on poorest air quality days is referred to as episode control. Its major advantage is that it focuses on the time periods when emission reductions are needed the most.

Albuquerque, New Mexico has a voluntary program whereby residents are notified of high concentrations by a pollution signal light on top of a building.[21] In Missoula, Montana a mandatory program has been established under which visible smoke from solid fuel chimneys is prohibited when winter particulate concentrations exceed 300 $\mu g/m^3$, unless the solid fuel burner is the sole source of heat.[22] When winter concentrations of particulate exceed 150 $\mu g/m^3$ residents are requested to voluntarily reduce or eliminate their solid fuel burning.

During winter 1981-82, particulate concentrations in Missoula exceeded 150 $\mu g/m^3$ on several occasions, but never exceeded 300 $\mu g/m^3$. Based on a statistical sampling of 194 households on 6 days/month, the Missoula Air Pollution Agency estimates that their requests for "voluntary cutbacks" were heeded in 36% of the households.[22] Missoula officials believe this estimate, based on sampling only afternoon burning is probably low since most burning occurs in the evening and another survey showed 70% of respondents stated they do not burn during alerts. Based on this experience, these authors estimate that a voluntary program, if well publicized, could reduce wood burning impacts by 33% or more on poor air quality days.

Based on ratio of peak days concentration to average winter day concentrations of 2.5*, the reduction in average winter particulate concentrations can be calculated, depending on the number of episode days.

# Episode Days In A Geographical Area	Calculation Basis	Estimated Reduction Average Winter Particulate Concentration From Wood Burning
4	(33% reduction) X 4 days/150 days * 2.5 Aver. Conc. =	2.2%
9	(33% reduction) X 9 days/150 days * 2.5 Aver. Conc. -	5%
12	(33% reduction) X 12 days/150 days * 2.5 Aver. Conc. =	6.7%
15	(33% reduction) X 15 days/150 days * 2.5 Aver. Conc. =	8.3%
18	(33% reduction) X 18 days/150 days * 2.5 Aver. Conc. =	10%
20	(33% reduction) X 20 days/150 days * 2.5 Aver. Conc. -	11.1%
25	(33% reduction) X 25 days/150 days * 2.5 Aver. Conc. =	13.9%

Thus for an area with typically 9 winter days with particulate concentrations exceeding 150 $\mu g/m^3$, a 33% reduction in wood burning (resulting from voluntary cessation of burning) could reduce the impacts from wood burning on those episode days by 33% and average winter wood burning impacts by 5%.

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*Larson first identified this relationship which resulted in setting 24-hour particulate standards at 2.5 times the level of annual particulate concentrations (150 vs 60 $\mu g/m^3$ TSP).

b. Emission Density Zoning

Emission density zoning could reduce particulate concentrations if it were applied to limit the number of installations of wood burning devices in future years in problem areas. However, for most political jurisdictions, we believe such a strategy would face major obstacles to its adoption and implementation. There appears to be widespread opposition to regulations which prohibit households from burning wood. Such sentiments would likely result in significant circumvention (i.e., individuals purchasing a stove and installing it without a "permit") and a herculean enforcement problem. Lastly, some State statutes such as those governing the Oregon Department of Environmental Quality, prohibit the regulation of household space heating devices. Accordingly, no practical emission reduction benefit was assumed for this strategy.

For those interested further in this approach, Appendix D projects how much emissions might be reduced for three cities in the Pacific Northwest in future years, if such a program were adopted and the compliance level were 50%.

C. IMPROVING RWC OPERATING PRACTICES

Operating procedures can have a dramatic influence on particulate emission rates. This section assesses the emission reduction potential from a) stove sizing, b) operating technique modifications which include discouraging airtight operation and charging larger pieces of wood, and c) household inspection programs for RWC households.

1. Initial Selection of Burning Unit - Sizing

Stove "down sizing" is sometimes advocated on the basis that a smaller stove can be burned "hotter" - air supply will not have to be restricted as much as in a larger stove to avoid overheating a room or house. The available literature on how emissions change with operator procedures has been reviewed in order to evaluate what emission benefits could be achieved by stove downsizing.

In summary, the chief benefit of downsizing derives from the fact that a smaller stove will have a smaller firebox. This means that average charge size is reduced. According to Butcher[18], emission rate is dependent on both charge size and burn rates as shown in the equation below:

$$\text{Emissions Rate (g/kg)} = k\ (m/q)$$

where m = wood charge size in kg
q = burn rate, in 10,000 Btu/hour

For a household which desires a certain rate of heat output, downsizing a stove does not materially effect that households desired level of heat output from the stove. Thus the "q" term in the equation should not change when a stove is downsized. However, since the emission rate is proportional to "m", or charge size, a smaller firebox stove can be assumed to have an emission rate that is proportionally lower to the reduction in firebox size. These issues are discussed in greater detail in Appendix D.

Day[24] has noted both that stove purchasers are tending to purchase smaller stoves and that manufacturers also are downsizing their model units. He projects that average stove firebox size will be reduced by 40% by 1990. Although the degree of downsizing that will occur cannot be known for certain, these authors arbitrarily assume that an educational program could result in additional downsizing of 10% by 1990 and an additional 5% by 2000 as compared to a base case without such an educational program. For the stove population, these assumptions yield an emission reduction of 10% by 1990 and an additional 5% by 2000.

For an area with 70% of RWC emissions from stoves, total RWC emissions would be reduced by 7% by 1990 and an additional 3.5% by 2000.

2. Operating Technique Modifications

a. Discouraging Airtight Operation of Stoves

Operators restrict airflow on stoves either to slow down the stove's rate of heat production to maintain comfortable room temperatures or to extend the length of time between stove refuelings. Combustion efficiency can decrease as a result of such action because the lack of sufficient oxygen in the combustion zone can result in less complete combustion and a higher emission rate.

However, when an operator changes to burn hotter (i.e., less air restriction) no benefit in reduced emissions per day is realized unless the operator reduces the number of hours per day that the stove is operated. This issue is discussed in detail in Appendix D Section C2a. For example, if the number of hours of operation remain the same, and an operator increases the burn rate by 50%, the emission rate will be decreased by 33% [(150/100)/150] on the gram/kg basis. However, the net emissions per day on a gram/day basis will stay constant, since 50% more wood will be burned, unless the operator reduces the number of hours of operation. One would expect that the hours of operation would need to be reduced in order to maintain a comfortable room temperature. However, comfort factors make it unlikely that a large portion of stove operators will be willing to shift normal operating patterns, for example, such that they would burn at a 50% higher burn rate for two-third's of the time and then not operate the stove for the normal last one-third of a burn cycle. The burn rates chosen by most operators are those which produce the desired level of constant heat output for the room in which the stove is located.

Since widespread increases in the burn rates used by operators appear unlikely, we assign no emission reduction credit to this strategy.

b. Charging Larger Pieces of Wood

Charging larger pieces of wood in a stove has resulted in a lower emission rate than burning smaller sized pieces of wood, in limited testing. Thinner pieces of wood have a large surface area to wood ratio which allows them to heat up relatively fast and release their volatiles at a fast rate. The high rate of volatile production can result in an oxygen deficiency in the combustion zone which results in less than complete combustion and higher particulate emission rates.

This phenomenon has been noted by both Cooke and Allen of Battelle[1m] and by Barnett[1i]. Barnett developed a best fit equation based on tests with a thin walled stove which relates particulate emission rates to log diameter. This is discussed in more detail in Appendix D. For wood in the size range between 2" and 6", increasing log diameter by about 2" results in 33% decrease in emission rates (i.e., 4-6" range is optimum).

An education program to convince operators to burn larger size pieces of wood appears to have strong potential as an education strategy, assuming additional testing confirms these preliminary findings. Unlike some other strategies to change operator behavior, there is no inconvenience disincentive for this change in operating practice. In fact, less splitting of wood requires less work. These authors estimate that an education program could result in 50% of operators increasing their average piece size by 2". For stoves, this means this strategy has an emission reduction potential of 16.5%.

Barnett's equation for predicting emission rates based on log diameter was developed based on stove burning rather than fireplace burning and thus this strategy only can be assumed to apply to stoves given current evidence. For an area where stoves account for 70% of RWC emissions, total RWC emissions are thus assumed to be reducible by 11.5% (33% X .5 X .7 = 11.55%). If later research were to show a similar relationship applies for fireplaces, then total RWC emissions would be assumed to be reducible by 16.5% by this strategy.

3. Periodic Inspection of RWC Equipment

Combustion equipment inspections can identify when equipment performance is deteriorating and promote more rapid restoration of the equipment to original performance levels. Higher combustion efficiency results in less air pollutant emissions.

Regarding whether inspection programs are a feasible means for reducing emissions from residential wood burning, we judge that political and legal obstacles make this strategy unlikely to be implemented in most communities. Oregon statutes prohibit the Department of Environmental Quality from regulating home space heating devices.[12] Aside from legal obstacles, many citizens are opposed to the concept of an inspector entering their dwelling and requiring equipment changes.

Potential benefits of an inspection program include the following:

- Safety

  33% of fires in Oregon in single family dwellings are associated with solid fuel heating equipment.[25] If an inspection program were to focus on safety aspects also, significant savings in personal property and lives could result.

- Maintaining Catalyst Performance

  Catalyst stoves can deteriorate with time in terms of the catalyst losing its efficiency because of deterioration of the catalyst coating. For example Corning Glass Works, a major manufacturer of stove catalysts, estimates their catalyst has a 6000 hour lifetime.[26] For a stove operated 20 hours/day for 5 months/year, this equates to a 2 year lifetime. In the event catalyst stoves ever account for a significant share of the stove population, an inspection program could help to ensure continued good combustion efficiency (i.e., reduced emissions) for this type of stove.

- Maintaining High Combustion Efficiency

  This benefit is speculative. For units with high (i.e., 95%) combustion efficiency with intricate air supply arrangements, maintenance may become more important to maintain this high combustion efficiency, than it is for less complex units with 80% combustion efficiency. As one example, units which channel some gases with combustion products through small air holes may experience "hole plugging" with time. An inspection program could identify and correct such problems.

- Advising Operators with "Smokiest Chimneys"

  Such a strategy is a combination of an inspection program with an educational program. Most of the benefits achievable by such a program would be associated with changes in operating procedures rather than equipment repair. It is probable that the 10% of operators who burn in a manner producing greatest emissions account for more than 20% of total emissions.

Despite these potential benefits, we assume political and legal obstacles will make this strategy unimplementable in most communities and thus assign no emission reduction credit to this strategy.

VI. SELECTION AND EVALUATION OF FINAL RWC CONTROL STRATEGIES

Section A describes the final list of RWC control strategies selected for evaluation and ranking. Section B describes the evaluation and ranking, which employs the full (three-step) Keppner-Tregoe evaluation process.

A. SELECTION OF FINAL RWC CONTROL STRATEGIES

Many combinations and variations of the RWC control strategy elements described and evaluated in Section IV could be used to control RWC impacts under a variety of local conditions. The list of RWC control strategies described in this section is considered to be a cross section of practical, effective strategies. They were selected to represent one or more of the following:

- Leading examples of RWC control strategies implemented elsewhere and which seem viable for implementation in other locations;
- Combinations of strategy elements recommended for evaluation by air pollution control agency staff, or study team members;
- Other combinations which seemed promising, based on the evaluation of individual control strategy elements (Section IV), RWC emissions reduction potential (Section V), and other considerations

The "availability" of some of the key elements of these strategies depends upon the adoption of local ordinances, or the establishment of financing programs - e.g., loans for weatherization. However, most of these proposed strategy elements have a precedent - e.g., an actual situation in which comparable ordinances or financing has been established. Accordingly, for purposes of this evaluation, these elements were assumed to be feasible.

Table 9 summarizes the fifteen RWC particulate control strategies selected for final evaluation using the full (three-step) Keppner-Tregoe process. The following subsections describe fifteen hypothetical RWC control strategies selected for final evaluation and ranking. The major elements of each strategy are briefly described, followed by additional comments.

1. Testing and Certification as Prerequisite to Sale or Installation of Wood Stove/Furnace

- Mandatory emissions testing and certification that emissions do not exceed standards ($\leq$ 5 g/kg) established by government, is required to allow sale or installation of wood stoves/furnaces.
- Government provides and operates facilities for testing, and adopts standard test procedure.
- Equipment certified for sale must be labeled as to its tested emission rate (g/kg of wood burned).
- Government publishes results of all tests and requires retailer to provide this information to prospective buyers.
- Government recoups some costs by charging fees for testing and certification to manufacturers.
- Applies to new and replacement or retrofit units anywhere within jurisdiction of adopting agency.
- Building permit required to install new or replacement stove/furnace. Only certified units can obtain permit.

This strategy is the first of five based on testing emissions from stoves/furnaces using standardized test procedures developed by government. In the first four of these, government also provides test facilities and conducts the testing, recouping

TABLE 9

Final Fifteen RWC Control Strategies Evaluated

Strategy #1	Testing/Certification as Prerequisite to Sales or Installation of New Stoves/Furnaces
Strategy #2	Strategy #1, with 33% Tax Credit ($400.00)
Strategy #3	Testing as Basis for Mandatory Labeling of New Stoves/ Furnaces Prior to Sales; Label Specifies Emissions Performance and Efficiency
Strategy #4	Strategy #3, with 33% Tax Credit ($400.00)
Strategy #5	Testing/Rating by RWC Industry Trade Association
Strategy #6	Mandatory Weatherization of All Households
Strategy #7	Mandatory Weatherization Only for Households Installing New Stove/Furnace
Strategy #8	Firewood Moisture Content Controls
Strategy #9	Stove Sizing
Strategy #10	Encourage Larger Firewood Piece Size
Strategy #11	Require Underfire Air Source for New Fireplaces
Strategy #12	Episode Controls
Strategy #13	Research and Development of Improved RWC Appliances and/or Practices
Strategy #14	Encourage Alternative Fuels
Strategy #15	Periodic Inspection of RWC Equipment

as much costs as possible by charging manufacturers to test their units. In the fifth strategy described below, emissions testing and labeling is carried out by an RWC Industry Trade Association.

The government established ceiling on emissions allowed is 5 g/kg of wood burned. Any stove/furnace must emit ≤ 5 g/kg to be certified, and only certified units may be sold or installed. The building permit required to install new, replacement, or retrofit units is intended to help enforce the strategy. The larger the geographic area in which this strategy was applied, the more effective it would be, with fewer opportunities for nonregulated markets to legally offer non-certified units.

Besides emissions, units could also be tested for combustion and thermal efficiencies, if desired.

2. Testing and Certification as Prerequisite to Sale or Installation Plus Tax Credit

- Same as Strategy #1, plus financial incentive in form of a tax credit.
- A $400.00 tax credit would be available to purchasers of new certified stoves/furnaces. This is 33% of the assumed average cost of $1200.00 for certified commercialized stoves/furnaces (see Appendix A, Section A).

Other types of financial incentives could be used - e.g., direct rebates of a portion of the purchase price. This tax credit was used in Section VA1 of this report, in estimating potential particulate emissions reductions achievable by various strategy approaches.

3. Testing as Basis for Mandatory Labeling Prior to Sales

- Mandatory testing to determine emissions of all stoves/ furnaces offered for sale.
- Government provides and operates facilities for testing, and adopts standard test procedure.
- All equipment sold must be labeled as to its tested emission rate (g/kg of wood burned).
- Government publishes results of all tests and requires retailers to provide this information to prospective buyers.
- Government recoups some costs by charging fees for testing and labeling.
- Applies to new and replacement or retrofit units anywhere in the jurisdiction of adopting agency.
- Enforcement by inspection of retail outlets for non-labeled units.

In this approach, all stoves/furnaces sold commercially must be tested by government and labeled as to their emissions rate (g/kg). This strategy relies on publicity to encourage consumers to purchase cleaner burning stoves and furnaces - i.e., determining and publicizing their emissions rates - much like publicizing automobile gasoline mileage test results.

However, whereas better gasoline mileage can save money for purchasers of autos, better emissions performance has little or no direct monetary payoff, except to the extent that higher combustion efficiency (less unburned exhaust products) increases overall efficiency and decreases the chance of house fire from excessive creosote build-up. Cleaner burning stoves may well be more expensive too, due to extra engineering or materials costs. Without the regulatory prohibition against selling units with high emissions, which strategies #1 & #2 have, consumers are free to purchase "dirtier" units, and probably would if they are cheaper. For those reasons, this testing/labeling strategy approach was assumed to be only 20% effective in reducing particulate emissions (see Section II Bla(3)). This is, only 1 in 5 new stoves/furnaces purchased under this strategy approach would be the cleaner units (i.e., emit ≤5 g/kg).

4. Testing/Mandatory Labeling Plus Tax Credit

- Same as Strategy #3, plus tax credit.
- A $400.00 (33%) tax credit would be available to purchasers of new stoves/furnaces which emit ≤5 g/kg of particulate.

The tax credit assumed to double the effectiveness of Strategy #3 (to 40%) but not equal the effectiveness of either strategy #1 or #2, which allow only certified stoves to be sold. Table 7 in Section V summarizes the estimated emissions reductions achievable for each of these first four strategies.

5. Testing/Rating By RWC Industry Trade Association

- RWC Industry Trade Association establishes facility to test burning units for emissions (and efficiency).
- All association members must participate and all of their commercially available units must be tested in order to be rated.
- Emissions rates (g/kg) must be labeled on burning units offered for sale.
- Trade Association must aggressively publicize its rating system and urge consumers to buy only rated units, and to minimize emissions, consistent with other desirable features - e.g., energy efficiency, heating needs, appearance, etc..
- Mandatory labeling also must include information on sizing burning units to match heating needs - i.e., how much space can be heated with unit, at various insulation levels.

- Association must publish information explaining importance of not oversizing heating units, and how to select proper size, using industry ratings.

This approach is like Strategy #3 above, but with industry instead of government implementing it. It has precedent in other trade association testing programs like the testing and rating of refrigeration equipment by the Air Conditioning and Refrigeration Institute and electrical equipment testing by the Underwriters Laboratory. This strategy approach calls for a vigorous industry effort to publicize test results, and even to encourage use of cleaner, properly used units. The traditionally neutral role of trade associations regarding purchase of particular classes of products might make this strategy hard to implement.

There also is no stove/furnace emission standard which is uniformly accepted, or government approved test procedures. This strategy relies upon the industry to monitor itself, and to develop internal means of encouraging cleaner burning stoves/furnaces. There is no effective way of forcing diligent effort by industry, except perhaps a commitment by government to do so if industry is not conscientious. This strategy would only be feasible on a national level, not local.

6. Weatherization of All Households

- Establish Energy Conservation/Air Quality office in government to coordinate and aggressively promote weatherization benefits, and help citizens get it done.
- Mandatory weatherization of all households to minimum cost-effective standards or better, beginning four years from effective date of enabling local ordinance. Prior to this, weatherization is voluntary, giving owners time to plan for compliance, and eager households the opportunity to obtain earlier benefits.

- Applicable to all residences up to 4-plex in size, and built prior to ... (date adequate insulation standards for new homes adopted in a given community).
- Weatherization requirement applies within 9 months of requested change in utility service and is the responsibility of the new owner, or landlord for a rental occupancy change; or at time of installation of a wood burning appliance in a residence.
- Applies to homes heated with electricity, oil, or natural gas.
- Utility inspects premises, assists owner in obtaining reputable contractor or in doing work himself. Utility inspects and approves final work and pays for it. Where weatherization is required due to new RWC appliance, utility helps determine proper sizing vs. insulation levels.
- Owner repays utility at a monthly rate such that his cost for weatherization plus heating fuel is not greater than his cost of fuel without weatherization.

In Section V weatherization is estimated to be one of the more effective strategy approaches to reducing RWC particulate emissions. This is the first of two weatherization strategies evaluated, both intended to reduce RWC emissions by reducing the space heating requirements of RWC-households. This particular approach would require eventual weatherization of all under insulated households, beginning four years after its adoption, allowing a voluntary phase in period. It is modeled after programs in Eugene and Portland, Oregon (see Section II F), and includes a leading role for both government and private utilities (oil, gas, and electric).

Its most controversial element could be its financing requirement that payments on no- or low-interest weatherization loans not exceed the previous cost of fuel without weatherization. Lenders might balk at such a flexible arrangement. Not much data is available yet from existing weatherization programs to reveal how much pre-weatherization fuel costs are actually lowered by insulation. However, an attractive financial incentive is needed to make the high initial cost of weatherization politically palatable as well as affordable to a large segment of the population. Weatherization has obvious energy conservation benefits, and has been promoted primarily for this purpose.

7. Mandatory Weatherization Only for Households Installing New Wood Stove/Furnace

- Weatherization to minimum cost-effective standards or cost effective level is required to install a new (including replacement) stove/furnace in a residence, hotel, or restaurant.
- Effective in four years from date of enabling ordinance enactment.
- Financing from low- or no-interest loans from government or utilities, who also provide technical assistance and referral to contractors or lenders.
- Require permit for stove/furnace installation, and evaluation of proper size for RWC equipment, based on insulation requirements, during permit review.

This approach would require weatherization only for households and commercial buildings installing new (including replacement) wood stoves/furnaces. Other RWC-households would be encouraged to voluntarily weatherize by allowing them to obtain the same financial aid. This approach is patterned after similar RWC controls adopted in Jackson County (Medford) Oregon (Section II E).

Since presumably fewer households would weatherize, less loan funds would be needed. Cost-effective insulation levels would be defined as those capable of cost payback in 5-7 years, based on saved conventional fuel costs. However, this approach unlike Strategy #6, does not try to assume that the monthly costs of weatherization (loan) plus conventional heating fuel costs do not exceed pre-weatherization fuel costs.

Enforcement by installation permit will be more or less effective depending upon the incentive for stove purchasers to circumvent this regulatory approach. If such persons feel unfairly singled out, and initial costs are too burdensome, circumvention may be high. This approach also may discourage replacement of older stoves/furnaces with newer, cleaner burning models, and/or discourage initial purchase of wood stoves/furnaces. These two factors would have opposite effects on RWC emissions reductions over time.

8. Firewood Moisture Content Control

- Government would undertake a major public relations campaign to promote proper seasoning of firewood, including use of broadcast media, brochures, and other forms of public information.
- Commercial firewood suppliers selling more than 10 cords per year would be required by law to state moisture content; moisture content meters would be made available to such parties at low or no cost.
- Cooperation of agencies or private companies who supply firewood would be sought - e.g., to encourage firewood gathering as far as possible in advance of the heating season.

- Information and possibly technical assistance in proper wood storage would be provided.

This strategy will reduce emissions from fireplaces as well as stoves/furnaces, although most of the emissions reductions are estimated to occur for stoves/furnaces. Section V estimates that the potential emission reductions from moisture control are among the highest of all strategy approaches evaluated (see Table 7).

This strategy's effectiveness depends on the degree to which public information can persuade people to dry their wood more effectively, thereby lowering the average moisture content of firewood used. In Section VB2 a a 2% reduction in wood moisture content was estimated to be reasonably achievable. This reduction was estimated to reduce RWC particulate emissions by 6.2% for an area like Portland, Oregon, with about 92% of the reductions coming from stove/furnace emissions. The high percentage of emissions reductions from stoves/furnaces occurs for several reasons, including: a) a high percentage (70%) of total RWC emissions is attributable to stoves/furnaces; and, b) stove emissions factors are more sensitive to moisture content than fireplace emissions rates (compare slopes of combustion efficiency curves in Figures 3 and 4 in Section V).

9. Stove Sizing

- Government would encourage proper sizing of new wood burning units, promoting the minimum size unit consistent with desired heat output and insulation requirements.
- Public information would be provided on the benefits and method of selecting a stove/furnace of appropriate size.

- Retailers of stoves/furnaces would be supplied with and required to make this information available to purchasers before they buy.
- A permit (e.g., building permit) would be required to install a wood stove/furnace. Part of the permit application process would be an evaluation of the size of the burning unit vis a vis the space it will heat.

Decreases in average house size, increasing stove/furnace costs, and increasing weatherization are among factors that will tend to naturally decrease the average size of wood burning units in the future. At least one national expert believes that the average stove firebox size will decrease by about 40% by 1990.[24] In Section V, decreases in average stove size of 10% by 1990 and 15% by 2000 were estimated to afford decreases in RWC particulate emissions of 7% and 10.5% respectively (Table 7).

This strategy potentially affords both significant emissions reductions and savings to those consumers who would otherwise have bought a larger, more expensive stove. Less creosote problems also should occur, because a properly sized stove can operate with more efficient combustion at a given burn rate. Some inconvenience may result in that smaller average wood charge size may require more frequent charging.

10. Encourage Larger Wood Piece Size

- Government would conduct research to confirm that increased average piece size reduces emissions, and to determine optimum piece size.
- Government would encourage burning of larger average size pieces of firewood through public information.

This strategy approach seems to offer the potential for significant (11-12%; Table 7) reductions in RWC emissions with no inconvenience to operators. However, since the emissions reductions estimate was based on a single emissions test conducted on an airtight stove[11], further research is needed to confirm or refute this potential before a major promotional effort is undertaken.

The strategy presently is assumed to reduce emissions only for stoves/furnaces not fireplaces, pending further research.

11. Require Fireplaces To Have Underfire Air Source

- Government would conduct research to confirm the emissions benefits of underfire air. If significant benefits are confirmed, government would require new fireplace installations to include underfire air devices.
- Government would require through building code or ordinance that new fireplaces include a simple device for introducing air under the combustion zone.

This strategy's emissions reduction benefits are limited to fireplaces, which will represent a decreasing fraction of total RWC emissions according to Task 3 analyses. The basis for the estimate in Section V of emissions reduction benefits from underfire air was a single, limited series of emissions tests.[17] Accordingly, additional tests of this effect should be done before it is promoted by government, especially for retrofit of existing fireplaces. However, its low cost and high potential emissions reduction, based on limited data, warrant priority research attention. Modification of a fireplace to have underfire air should cost less than $100.00.

12. Episode Controls

- Voluntary curtailment of RWC whenever 24-hour particulate levels (TSP) exceed established levels: TSP 150 $\mu g/m^3$, or 60 $\mu g/m^3$ of "respirable" particulate (≤ 2 μm).
- Mandatory curtailment of RWC during such episodes if voluntary approach does not prevent further air quality deterioration during the next 3 years - i.e., if peak and average pollutant levels worsen.
- Enforcement by visual opacity checks (day only) and revocation of permit required for installation of RWC equipment.
- Public education (media; brochure) to promote positive attitude towards program which could increase compliance.

This strategy is based on a similar program (see Section II D) adopted in Missoula, Montana and in Vail, Colorado. Medford, Oregon also has adopted similar episode controls as part of a multi-faceted RWC control program (see Section II E). The chief benefit of this strategy is emissions reductions on worst air quality days, estimated at 33% per episode day in Section V. The extent to which such air intermittent strategy would reduce seasonal or annual average emissions depends upon the number of episode days per season or per year.

13. Research and Development of Improved RWC Equipment or Operating Procedures

- Government would undertake and/or promote private or academic research and development of improved RWC appliances and practices and actively disseminate the resulting information to private parties for commercialization, and to the general public to encourage use of improved RWC appliances and practices.

- Government provides a free, fully staffed emissions test facility, and develops standardized test procedures. These are made available at low cost for promising research, along with technical advice and assistance, to researchers with promising ideas.
- Government offers attractive monetary awards ($50,000 above costs) to designer or manufacturer of first wood burning stove that emits ≤ 1 g/kg of particulates, with an overall efficiency in excess of 60%, and costs $1000 or less.
- A similar award is offered for developing a simple inexpensive, reproducible emissions test for RWC appliances.
- Other incentives include tax credits for research or investment in RWC emissions test equipment, or for approved-in-advance research which develops less polluting alternatives to RWC.
- Research also could address improving fuel characteristics, to develop "smokeless" fuels.

This strategy approach emphasizes encouragement and financial support of high quality research to develop less polluting residential wood burning equipment or fuels, better emissions test procedures, and improved operator practices. Like much research, it could be expensive with uncertain results. However, it directly addresses the plain need for more hard information on the relationship of wood burning emissions to many key variables such as stove design, fuel characteristics, and operator practices. Many of the analyses and assumptions described in this report illustrate the scarcity of emissions test data and systematic comparisons of alternative RWC equipment, fuels, or practices.

Filling these large information gaps will depend most upon the development of reliable, inexpensive test procedures for units. These are needed to encourage innovative designs, by providing inexpensive information to guide design/development of improved equipment/practices. Research incentives, such as the prizes described above, would be supplemented by active promotion and encouragement of promising research, through research grants, seminars, publication of results, etc..

No attempt was made to estimate potential RWC emissions reductions attributable to R&D efforts because they are too unpredictable, and because R&D funding would be especially hard to obtain in the present sluggish or depressed economy.

14. Encouraging Alternative Fuels

- To discourage RWC for space heating, the government could undertake efforts to encourage alternative fuels use, including the following measures:
  - Require utilities to offer lower rates for space heating with oil, natural gas, or electricity, by allowing or encouraging compensating rate increases for other uses.
  - Encourage lifeline electricity rates.
  - Promote the use of passive solar energy for space heating, natural gas radiant heaters or fireplaces.
- Restrict firewood supply by:
  - Limiting access to state and federal lands for firewood cutting to spring and summer.
  - Limiting total firewood removal from state and federal lands, based on analysis of air quality impacts of local use.
- Encourage alternative uses of logging residues - e.g., subsidizing pilot programs for use in pulp and paper making, or thermal power plants of appropriate scale.

This is the only strategy approach that directly attempts to discourage RWC over the long-term - i.e., attempts to discourage new RWC-households and induce existing RWC-households to cease RWC or to rely more on other means of space heating. The first three measures mentioned above provide positive alternatives to RWC by encouraging the use of solar energy or convention fuels. The last three measures simply restrict wood supply directly, which could prove unpopular, and hence politically difficult to implement. Encouragement of conventional fuels - especially oil - is contrary to national policy of increasing energy independence. However, conventional fuel use may be less polluting, and offer more stable supply than firewood.

15. Periodic Inspection of RWC Equipment

- Require annual inspection and maintenance of residential wood-fired space heaters, by professional chimney sweeps in designated problem areas.
- Inspections would test emissions of home heating equipment and evaluate safety.
- Identified equipment maintenance requirements must be corrected within 30 days to avoid civil penalty (up to $500.00) and reporting of the deficiencies to fire insurance companies.
- Inspectors also could provide information and technical assistance on RWC practices such as wood storage and stove operation.
- Roving inspectors could respond to visual evidence of poor RWC practices, or complaints of same.

Some European countries like West Germany (Section II C) have long had residential inspection of large conventional fueled residential space heating devices. Extrapolating such a program to solid fuels (wood, coal) may prove less productive since a solid fueled stove cannot be cleaned and tuned for improved fuel efficiency like an oil burner can. Wood burning stoves equipped with a catalyst unit to enhance combustion could be checked for remaining catalyst life/effectiveness to assure more timely replacement. Also, as stoves become more sophisticated, the need for periodic inspection/maintenance increases, if high combustion efficiency is to be maintained.

Inspection for safety purpose - e.g., creosote build-up in flue - could be the cornerstone of this approach, since so many home fires can be associated with RWC.[25]

Inspection may be most effective where the number and type of RWC devices is controlled - e.g., where only tested/certified units can be sold or installed, or for subdivisions or other residential developments where the developer can impose restrictions on RWC.

. . . .

The Section IV evaluations indicated that the most effective types of RWC controls include: proper sizing of wood burning units, home weatherization, emissions testing and certification of RWC appliances as a condition of sale and use, incentives to use cleaner burning appliances, and wood moisture controls. The fifteen final strategies utilize all of these approaches and various combinations with supplementary strategy elements.

For example, the first five final strategies are based upon testing and certification or labeling of RWC appliances, and in several cases, compliance with minimum emissions standards is required. Several different weatherization approaches are proposed - one requiring weatherization of all households (#6), another requiring it only to install a new RWC appliance (#7). Proper sizing of RWC burning units is emphasized in the first seven strategies. Likewise, incentives and wood moisture controls are emphasized in several strategies.

Disincentives to RWC also could be employed - e.g., an emissions tax to discourage use of more polluting RWC appliances. This was not included in the final strategies evaluated because the price elasticity of demand was too difficult to determine. Also one would expect the outcome or benefits to be similar to those obtained with tax credits (Strategies #2, #4). Strategy #14 contains the disincentive of restricting firewood supply.

B. KEPPNER-TREGOE EVALUATION OF FINAL RWC CONTROL STRATEGIES

The full three-step Keppner-Tregoe evaluation process described in Section III was applied to the fifteen final RWC control strategies summarized in Figure 6. All strategies satisfied all MUST criteria, with one major caveat. Full implementation of a number of the strategies would require the establishment of financing programs or additional legal authority, through adoption of local ordinances or possibly state laws. Adequate legal authority, and commitments of resources to implement proposed RWC control programs would be necessary to include any of them in an air pollution control program for a local area that could be officially approved by the U.S. Environmental Protection Agency as "meeting all legal requirements established by the Clean Air Act" (MUST criteria #2).

1. Ranking the Final Strategies Using WANT Criteria and Risk Factors

The evaluation of all fifteen strategies versus the twelve WANT criteria is documented in Appendix E. This appendix contains individual scores assigned to each strategy, for each WANT criteria (Appendix E, Table E2), and explains some of the major reasons for the scores given. It also describes the major adverse

FIGURE 6

Summary for Fifteen Final RWC Control Strategies
of the Keppner-Tregoe Ranking
vs
WANT Criteria and Major Strategy Costs and Benefits*

RWC Control Strategy[1]	Keppner-Treoge Ranking vs WANT Criteria[2] (Rank)	Keppner-Treoge Ranking vs WANT Criteria[2] (Points)	Estimated Implementation Costs[3] ($)	Benefits[3,4] of Implementation
Testing/Certification; Tax Credit (Strategy #2)	1	535	-$50,000[5] -$130,000/year[6] -$1.8 - 7.2 million per year tax credits[7]	-Potential Emissions Reduction (%): 1985 1990 1995 2000 3 11 30 39
Testing/Certification (Strategy #1)	2	508	-$130,000/year[6] -$50,000[5]	-Potential Emissions Reduction (%): 1985 1990 1995 2000 2 8 22 30
Larger Firewood Piece Size (Strategy #10)	3	490	-$45,000/year[6]	-Potential Emissions Reduction: 11.5%
Testing/Labeling; Tax Credit (Strategy #4)	4	469	-$50,000[5] -$160,000/year[6] -$0.8 - 3.2 million per year tax credits[7]	-Potential Emissions Reduction (%): 1985 1990 1995 2000 1 5 15 21

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[1] From Table 9.

[2] From Appendix E.

[3] From Appendix F.

[4] From Appendix D.

[5] One time start-up costs.

[6] Annual administrative costs.

[7] Based on $400 per certified unit; 5,000 to 20,000 total units sold, and % of total units sold assumed to be certified units.

*Refer to discussion in text regarding assumptions used in arriving at rankings.

FIGURE 6 (Cont.)

RWC Control Strategy[1]	Keppner-Tregoe Ranking vs WANT Criteria[2] (Rank)	(Points)	Estimated Implementation Costs[3] ($)	Benefits[3,4] of Implementation
Encourage Alternate Fuels (Strategy #14)	5	458	Not quantifiable	Not quantifiable
Research and Development (Strategy #13)	6	445	Not quantifiable	Not quantifiable; but significant - can enable many other strategies to have their efficiencies improved.
Stove Sizing (Strategy #9)	7	443	-$45,000/year[6]	-Potential Emission Reduction (%): 1990 2000 7% 10.5%
Testing/Labeling (Strategy #3)	8	438	-$50,000[5] -$130,000/year[6]	-Potential Emission Reduction (%): 1985 1990 1995 2000 1 3 8 11
Mandatory Weatherization for All Households (Strategy #6)	9	432	-$150,000 to $600,000[6] -$1,400 to $1,500 per household	-Potential Emission Reduction (%): 1990 1995 3.5 - 16.0[8] 7.0 - 16.0[8]
Stove Testing/Rating by Trade Association (Strategy #5)	10	422	-$50,000/year[5,7] -$130,000/year[6,7]	-Potential Emission Reduction (%): 1985 1990 1995 2000 1 3 8 11

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[1] From Table 9.

[2] From Appendix E.

[3] From Appendix F.

[4] From Appendix D.

[5] One time start-up costs.

[6] Annual administrative costs.

[7] Costs paid by private sector.

[8] Emissions reduction depends on assumptions used regarding changes in RWC practices after weatherization.

FIGURE 6 (Cont.)

RWC Control Strategy[1]	Keppner-Tregoe Ranking vs WANT Criteria[2] (Rank)	(Points)	Estimated Implementation Costs[3] ($)	Benefits[3,4] of Implementation
Mandatory Weatherization for New/Replacement RWC Households (Strategy #7)	11	411	-$20,000 to $80,000 per year[6] -$1,450 per household.	-Potential Emission Reduction (%): 1990: 3.5 - 16.0[7] 1995: 7.0 - 16.0[7]
Moisture Controls (Strategy #8)	12	400	-$45,000/year[6]	6.2%
Episode Controls (Strategy #12)	13	381	-$25,000[5] -$8,000/year[6]	33% reduction on Episode days
Annual Inspection (Strategy #15)	14	321	-$.75 to 1.5 million/year for an area with 50,000 to 100,000 stoves.[6]	-No emissions reductions credited. -18% less home fires (est.). -Lower fire insurance costs.
Underfire Air Controls for New Fireplaces (Strategy #11)	15		-$.1 to .3 million/year installation costs for an area with 1,000-3,000 new fireplaces per year.	-Potential Emission Reduction (%): 1990: 1% 2000: 2%

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[1] From Table 9.

[2] From Appendix E.

[3] From Appendix F.

[4] From Appendix D.

[5] One time start-up costs.

[6] Annual administrative costs.

[7] Emissions reduction depends on assumptions used for changes in RWC operation after weatherization.

consequences (Risk Factors) identified with implementing each strategy (Appendix E, Figure E1). These were not considered sufficiently problematic to warrant changing the ranking established by the total WANT criteria scores assigned to each strategy.

The final ranking of all fifteen strategies versus all twelve WANT criteria is shown in Figure 6. This represents the relative satisfaction of all twelve WANT criteria simultaneously - not the relative RWC emissions reduction potential which was only one of the twelve criteria.

C. SELECTED COSTS AND BENEFITS OF FINAL RWC CONTROL STRATEGIES

As described in Section III E, as a companion analysis to the Keppner-Tregoe evaluation of strategies, selected costs and benefits of implementing the strategies were considered. For the fifteen final RWC control strategies, the estimation of such costs and benefits is described in Appendix F. The results of this analysis are the costs and benefits summarized in Figure 6.

Cost estimates presented include mostly administrative costs. These are often quite speculative, although they are based on experience from existing agency programs, or expert opinion, where such information was available. While public and private sector costs were considered, no extensive data gathering on this was feasible for this study, so the resulting cost estimates are preliminary and approximate. Nevertheless, they serve to indicate gross differences or similarities in the relative administrative costs of implementing various strategies.

The benefits summarized are intended to highlight the major achievements anticipated by implementing each strategy. The first such achievement is a quantitative estimate, if available, of the amount by which the strategy could reduce RWC emissions, either in the short- or long-term. Section V (and Appendix D) is the source of these estimates. Other benefits include achievements such as energy conservation, safety enhancement, avoiding inconvenience, etc.. Benefits not quantifiable include the incremental health and visiblity benefits from the pollution avoided.

Figure 6 summarizes the costs and benefits estimated in Appendix F, along with the overall ranking of the 15 strategies against all WANT criteria.

D. FINDINGS AND CONCLUSIONS

1. Best Emissions Reductions

The two strategies which ranked highest against all WANT criteria (Strategies #2 and #1) also provide the highest percentage reduction in RWC particulate emissions - 39% and 30% respectively, by the year 2000. Both involve mandatory testing/certification and prohibition of the sale of wood stove/furnace models which can't comply with government emission standards (≤ 5 g/kg suggested standard).

This strategy approach is very effective over time in lowering emissions, as these new units replace existing stoves/furnaces which emit, on the average, four times as much particulate pollution. This approach requires years for its maximum benefits to accummulate.

Both strategies restrict consumer choices dramatically, which could produce public opposition, if such limitations are perceived to have caused the price of remaining stoves to rise unreasonably. To help avoid this the top ranked strategy (#2) includes a financial incentive (33% tax credit estimated at $400/unit in 1984). This in turn makes this the most expensive strategy of all those reviewed, with likely annual costs (tax revenues foregone) in the millions of dollars for a program of statewide scope.

Such costs seem to be appropriate and manageable. Oregon has spent hundreds of millions of dollars over the last decade in pollution control tax credits for industrial control equipment. The growing evidence that RWC particulate emissions approach or surpass those of industrial sources in many cases (e.g., Portland, Oregon) argues strongly for shifting some pollution control tax credit resources to address RWC.

Another potential hurdle in implementing the testing/certification approach are possible difficulties in enacting legal authority to prohibit commercial sales of non-certified burning units.

2. Least Cost Emission Reductions

Based on the analyses (and assumptions) in this report, a group of strategies emerge which potentially offer significant RWC emissions reductions, with minimal cost and inconvenience, and high public acceptance. They would appear to offer by far the most substantial RWC emissions reductions, at the least cost - especially if they are implemented in combination, as explained below.

There is one major caveat - the estimated emission reductions from these strategies have high uncertainty for two reasons. First, their research basis is thin. Second, they rely on public information to change RWC practices, and human behavior is notably uncertain and difficult to predict.

The strategies with their estimated RWC emissions reductions in parenthesis include: encouraging larger firewood piece size (11.5%), moisture content (6.2%), stove sizing (7-10%), and; episode controls (33% on episode days). All are based on public education. The first three could be jointly implemented with annual administrative costs that are modest (estimated less than $100,000 in Appendix F) compared with the other strategies evaluated here. The combined emissions reductions of these three strategies is 23% by about 1990 [(1.0 - .062)(1.0 - .115)(1.0 - .07) = .77]. This surpasses both of the top ranked (testing/certification) strategies, which are estimated to achieve 12-17% emissions reductions by 1990 at twice the cost, or much higher, if tax credits or other financial incentives are offered.

However, the equations used to estimate emissions reductions from all three strategies are based on limited lab tests by a single researcher (different in each case), although the general phenomena may have been observed by several researchers. These strategies are thus prime candidates for further research to determine whether they really do offer the most cost-effective RWC controls.

3. Research and Development

Despite the fact that no emission reduction estimate could be made for this strategy, it still ranked highly (5th overall) in the Keppner-Tregoe process. It is the key which could open the door to emission reductions from a wide range of strategies. This point is illustrated in the section above which discusses educational strategies to change operating practices. These strategies may well be the most cost-effective strategies for reducing RWC emissions over the next 10-20 years, but additional research is needed to verify this.

Of all research and development funding categories, the greatest need appears to be for the development of simpler and less expensive emission measuring techniques for RWC. This would facilitate not only testing/certification or testing/labeling strategies, but also help researchers refine the basic equations which describe how RWC emissions are affected by key variables such as moisture content, piece size and charge size.

4. Emissions Testing/Labeling Strategies

Three testing/labeling strategies (#3,#4, and #5) ranked 8th, 4th, and 11th respectively in the overall WANT criteria ranking.

All offer potentially significant emissions reductions by 1990-2000. The largest reduction occurs with a significant financial incentive (33% tax credit) which also greatly increases the program costs.

The emissions reduction benefits are significantly less than those from Strategies #1 and #2 which restricted sales to certified units only. This dramatic limitation on consumer choice was at once a major strength and liability for the testing/certification strategies. The three testing/labeling strategies preserve consumer choice. In so doing they are likely to be much less effective in promoting the purchase and installation of stoves emitting ≤ 5 g/kg. Even with the tax credit option, there are likely to be cheaper stoves available with much poorer emissions characteristics.

5. Weatherization

The two weatherization strategies -- mandatory weatherization for all households (#6), and mandatory weatherization only for households purchasing new stoves (#7) -- were ranked 9th and 12th. Both were judged to have relatively poor public acceptance due to their mandatory nature, and high initial cost (despite eventual "payback" through fuel savings).

In the short-term, weatherization of a household may not yield an emission reduction equivalent to the reduction in heat (Btu) requirements, because 1) the operator may continue to burn as much wood as before and rely less on conventional fuels, 2) the operator may burn at a slower burn rate with a higher emission factor, and 3) most operators will not immediately replace their existing stove with a smaller less-polluting unit.

In the longer term, when the owner of a weatherized home replaces his existing stove, additional emission reduction benefits may occur, if a sizing education program convinces him to purchase a smaller stove, which generally will have a lower particulate emission factor.

6. Public Acceptance

The strategies rated most acceptable to the public at large and to RWC households in particular generally were those involving the least inconvenience and/or costs. For example, Strategy #10 (increasing firewood piece size) ranked third overall, with the highest possible scores in "public acceptance" and "minimizing consumer costs". It costs individuals nothing, and reduces the work of splitting wood, while affording significant (11.5%) estimated emissions reductions.

The labeling strategies (#3, #4, and #5) ranked next highest in public acceptance. They provide information which helps the consumer choose a new stove, without limiting his choices or raising stove prices. The version with a subsidy (Strategy #4) ranked highest of these three.

Ranking similarly high in public acceptance were moisture controls (Strategy #8) and stove sizing (#9). Both provide information and rely on voluntary compliance with little or no enforcement pressure (stove sizing involves an installation permit review process). Episode controls (Strategy #12) which ranks almost as high in public acceptance, also would rely on voluntary compliance except under very severe pollution levels.

Research and development easily ranks high in public acceptance, offending no one.

7. Lowest Ranked Strategies

The strategies which ranked last under the Keppner-Tregoe analysis were fireplace underfire air and periodic inspection. Fireplace underfire air has been reported to reduce emissions by 40%, but this is based on a single lab test. This strategy does not address the largest category of RWC emissions at all - stove emissions - and it applies only to new fireplaces. It was not assumed to have high public acceptance.

Periodic inspection, although it has significant safety benefits, was not assumed to have any certain emission reduction benefits in most cases. The inspection strategy appeared likely to have emission reduction potential only in areas with either 1) a high fraction of catalyst stoves (catalyst lifetimes are about 2 years), 2) a high fraction of new technology high efficiency units (more sophisticated units may be more likely to need maintenance to maintain high performance), or 3) a limited number of stove models, since inspectors then would have greater potential for recognizing relatively poor performance and maintenance needs. Periodic inspections was assumed to have poor public acceptance.

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APPENDICES A thru F

Appendix A - Keppner-Tregoe Evaluation Process

Appendix B - RWC Control Strategy Elements

Appendix C - Ranking RWC Control Strategy Elements vs WANT Criteria

Appendix D - Estimated RWC Emissions Reduction Potential of Generic Control Strategy Approaches

Appendix E - Ranking Final RWC Control Strategies vs WANT Criteria

Appendix F - Selected Costs and Benefits of Final RWC Control Strategies

APPENDIX A

Keppner-Tregoe Evaluation Process

This appendix describes: the reasons for selecting the MUST criteria and some of the WANT criteria used in this analysis (Section I), and; the method of paired comparison used to assign Weighting Factors to WANT criteria (Section II).

I. MUST AND WANT CRITERIA RATIONALE

In establishing MUST criteria, several seemed automatic -- e.g., reduction of RWC pollution impacts, conformance to Clean Air Act requirements, and maintenance of safety characteristics of RWC appliances. The Clean Air Act requires areas which exceed ambient air quality standards to be addressed in State Implementation Plans (SIPs). SIPs must propose enough emissions reductions from point and area sources to achieve compliance with the Ambient Air Quality Standards. Adequate legal authority to control these targeted sources must be demonstrated in SIPs. Accordingly, control strategies considered in this analysis should either be implementable under existing state or local legal authority, or any needed changes in state statute or local ordinances should be acknowledged.

The effectiveness of a proposed strategy must be documentable for SIP purposes, including quantitative estimates of emissions reductions. To make significant reductions in emissions from the areawide RWC source, a strategy must be widely applicable - i.e., it must affect a significant portion of all wood burning practices or appliances. Furthermore, it should be implementable within a relatively short time, in order to minimize either the purchase of inferior new or replacement RWC appliances, or the prolonged continuation of inferior RWC practices. An exception to this would be a strategy with very significant long-term benefits. As already mentioned, any changes in RWC appliances or practices to reduce air pollution cannot be made at the expense of safety factors.

Consequently, the MUST criteria presented in Table 1 of the report text were selected for use in evaluating proposed RWC air pollution control strategies.

WANT criteria can and should include some MUST criteria, or aspects of MUST criteria. This allows evaluation of the extent to which some strategies will satisfy these important criteria better than other strategies. For example, MUST criteria #1 (Table 1) requires that proposed strategies reduce RWC air pollution impacts. WANT criteria #1 and #2 (see Table 2) reflect how well proposed strategies reduce RWC air pollution by evaluating how well each proposed strategy does two things: 1) reduces the average amount of RWC emissions per household, and; 2) discourages new RWC households, or encourages existing RWC households to stop RWC.

Use of WANT criteria #2 does not imply that strategies should be designed to discourage RWC activity itself. This would undoubtedly be widely viewed as unwanted intrusion by government upon individual freedom of choice. Also, states like Oregon expressly exempt individual households from direct state agency regulation of air contaminant emissions.[12] This criteria is simply an appropriate parameter for evaluating the effects of a given strategy, in discouraging new RWC households or encouraging existing RWC households to discontinue RWC.

The most effective RWC control strategies will be those which effect maximum reduction of RWC emissions with minimum impact on individual freedom of choice, cost, and inconvenience -- i.e., with maximum public acceptance. Accordingly, a WANT criteria (#4) has been included to evaluate public acceptance of proposed strategies. It is intended to indicate several different things. One is the anticipated public perception of whether a proposed strategy is an appropriate, or at least tolerable, level of regulation for dealing with air pollution problems related to RWC. Another is the anticipated acceptance by affected individuals of whatever inconvenience the proposed strategy might cause them. Inconvenience here means extra work, not costs which are covered under WANT criteria #6.

The perceived costs of installing and using RWC are likely to be the overriding factors influencing individual consumer decisions. A University of Idaho study[27] found that the main reason given by people for using RWC was to "save money". A Dartmouth study[28] which modeled New England wood fuel use, portrays the price of wood and conventional fuels as the most influential factors in promoting or suppressing RWC. Proposed RWC strategies which exert their effect by making RWC more costly may be the most effective strategy of all. However, strategies which force large added costs on RWC users could generate significant political opposition. Accordingly, strategies which obtain significant RWC emissions reductions while minimizing added consumer costs are preferred.

Many WANT criteria could be based on cost considerations. For example, separate WANT criteria could call for minimizing capital costs and operating costs of RWC to homeowners; minimizing similar costs to RWC appliance manufacturers; and minimizing agency costs to regulate RWC. However, if too many WANT criteria were based on various RWC costs, combined with the separate estimates of strategy costs called for in Step #6 of the overall evaluation process, too much weight might be placed on cost factors, or cost considerations might be too heavy in the wrong part of the strategy evaluation process. Accordingly, recognizing the strong influence of consumer cost on RWC control strategy effectiveness, a single WANT criteria (#6) is included, based on consumer costs. It is intended to represent the assumption that the more a proposed strategy increases the consumer costs of RWC, the more it will discourage RWC altogether. It also assumes that increased costs incurred by the private sector, as a result of a proposed strategy, will be passed on to the consumer.

Agency costs of regulating RWC are a consideration under WANT criteria #9, which deals with the administrative feasibility of proposed RWC control strategies. Other considerations under this criteria include the degree to which proposed strategies: a) could be implemented rapidly, b) conform to Clean Air Act and EPA requirements,

c) have effects which can be documented for purposes of inclusion in State Implementation Plans (SIPs), d) can be accepted (i.e., not strongly resisted) by regulated parties, and e) require willing participation by key parties which might not be forthcoming -- e.g., low interest loans by financial institutions to subsidize home weatherization.

Other WANT criteria address whether proposed control strategies: a) discourage the use of the worst polluting RWC appliances or practices, b) utilize proven technology or encourage innovative technology, c) are widely applicable to RWC appliances or practices, d) minimize interference in the free market, and e) promote energy conservation and use of less polluting renewable energy resources, and f) have minimal probability of circumvention. In this report use of renewable resources is meant to exclude the promotion of wood fuel for RWC, because this would contradict the purpose of RWC control strategies.

Table 2 in the text presents WANT criteria selected for use in evaluating proposed RWC control strategies.

II. WEIGHTING FACTORS FOR WANT CRITERIA

An analytic tool called paired comparison was used to develop Weighting Factors for all WANT criteria. In this technique, each WANT criteria is paired with each other WANT criteria separately. For each pair a judgement is made as to which criteria is most desirable or important. Then a score 1-3 is given to represent their relative difference in importance using the following scheme.

Relative Importance	Score
Little Difference	1
Some Difference	2
Great Difference	3

Figure A1 is a worksheet showing the results of the paired comparison analysis of the 12 WANT criteria listed (Table 2 in the text) above. In each box, the letter refers to the WANT criteria considered most important in that paired comparison. The number in each box is the score indicating the difference in importance of the two criteria. Scores are summed for each WANT criteria (letter), and converted into Weighting Factors, as shown in Figure A1. For the 12 WANT criteria, Weighting Factors will range from 1 to 13.

FIGURE A1

Paired Comparison Work Sheet

WANT Criteria		A	B	C	D	E	F	G	H	I	J	K	L
Reduce RWC emissions/household	A												
Reduce No. of RWC households	B	A1											
Maximum public acceptance	C	A1	B1										
Minimum consumer cost	D	A2	B2	C1									
Discourage Worst Appliances/Practices	E	A2	B2	C1	E2								
Maximum agency admin. feasibility	F	A3	B2	C2	D2	E2							
Use proven technology	G	A3	B3	C2	D1	E2	G1						
Encourage innovative technology	H	A3	B3	C2	D2	E3	F1	G2					
Widely applicable	I	A1	B1	C1	I1	I1	I2	I2	I3				
Minimize free mkt. interference	J	A3	B3	C3	D2	E2	F1	G2	H1	I3			
Promote conservation/renewables	K	A3	B3	C3	D3	E3	F2	G2	H1	I3	J1		
Minimize Circumvention	L	A2	B2	C1	L1	E1	L1	G1	L2	I2	L2	L2	
		A	B	C	D	E	F	G	H	I	J	K	L
Total Points (125)		23	22	15	10	15	4	8	2	17	1	0	8
Fraction of Points		.184	.176	.120	.080	.120	.032	.064	.016	.136	.008	.000	.064
Factor Ranking		1	2	4	6	4	9	7	10	3	11	12	7
Weighting Factor		13	13	9	6	9	3	5	2	10	2	1	4

Instructions

For each pair of WANT criteria compared, place the letter of the more important criteria in the square, followed by one of the following scores, based on an assessment of the difference in importance of the two criteria.

Score	
1	Little Difference
2	Some Difference
3	Great Difference

Sum the total points scored for each WANT criteria (letter); calculate Weighting Factors.

APPENDIX B

RWC Control Strategy Elements

This appendix lists the seventy-five RWC control strategy elements compiled for initial screening and evaluating, organized in the following format:

I. Strategies to reduce emissions by improved burning unit design
II. Strategies to reduce emissions by reducing wood usage
III. Strategies to reduce emissions by focusing on operating procedures

Within these categories, strategies can be organized by the methods of achieving these strategies, namely:

A. Regulations requiring compliance with various wood burning rules
B. Market incentives to achieve the strategies
C. Information distribution/technology transfer to speed development and implementation of strategies

I. BURNING UNIT DESIGN

A. Regulations

1. Government-required certification programs which set burning unit emission standards.
    a. For new installations
    b. For existing units (retrofits)
2. Government required rating programs under which woodburning units sold must be rated for emissions.

B. Market Incentives

1. Government subsidies for purchase of cleaner burning units.
    a. Subsidies to purchasers
        1. For new installations
        2. For existing installations (retrofits)
        3. Variable subsidy proportional to clean burning characteristics
        4. Subsidy of X amount for all units cleaner than certain emission rate
    b. Subsidies to manufacturers
        1. Increased tax advantages for emissions related research
            a. Basic research
            b. Pollution measuring equipment only
        2. Increased tax disadvantages for companies in proportion to the increasing pollution characteristics of their burning units.
    c. Sponsor design competition with $50,000 prize to first designer of a burning unit that costs less than $1000.00 (commercially) and emits at a rate less than 1 g/kg.
    d. Offer $50,000 prize to first designer of a test procedure system that costs less than $100.00 per test.

C. Technology Transfer

1. Government agency provides funds to help reduce the cost of emissions testing.
    a. Free fully-staffed testing facility
    b. Tax credits on emissions testing equipment and/or services
    c. Funds to develop standardized, simplified and less expensive emissions test procedure (now $2000 per test)

2. Trade Association emissions rating program
    a. Voluntary program for submitted burning units
    b. Mandatory program wherein all trade association members must submit to testing on all models
    c. Mandatory program wherein a manufacturer can only participate in the program if all unit types produced by the manufacturer are tested
3. Disseminate design information
    a. Government funds to publish one-time or periodic updates on burning unit design considerations/research
    b. Trade Association funds to publish one-time or periodic updates on burning unit design considerations/research

II. REDUCING WOOD USAGE

A. Regulations

1. Weatherization requirements so heating requirement is reduced.
    a. Allow new installations only in dwellings which are highly weatherized
    b. Require all dwellings to be weatherized to a cost effective level (5-7 years payback) within 5 years or after resale (as in the Portland Energy Policy)
    c. Tax credits from government to offset some or all of the costs.
    d. Require utilities to assist in paying for weatherization.
2. Limit access to wood from federal lands.
    a. Environmental Impact Statement requirement - Require the USFS and BLM to conduct an environmental impact assessment of the air quality consequences of their

releasing inexpensive wood which when burned in urban areas, can in aggregate constitute the single largest source of particulates.

   b. USFS/BLM limits on wood use
      1. Allow only X cords cut per year based on air quality
      2. Allow only X cords per cutting permit (e.g., 2.5 cords rather than the 4+ cords which might be needed to heat a poorly insulated house,
      3. Stagger wood cutting periods to help assure drying of wood
3. Emission density zoning.
   a. Allow only X burning unit installations per square mile based on area dispersion capacity
   b. Allow only X cords of wood to be burned per square mile based on area dispersion capacity
4. Burning unit efficiency
   a. Allow new installations only if unit will provide a net substantial heat gain (likely implies glass doors for fireplaces)
   b. Efficiency certification-allow new installations only if unit efficiency exceeds certain requirements

B. Market Incentives

1. Government subsidies for weatherization.
   a. Only in areas with severe pollution potential
   b. In all areas
2. Increase wood prices to residential users.
   a. Subsidies for industrial use of wood to enable industrial users to outbid residential users for available wood
   b. Increase USFS/BLM wood cutting permit fees

3. Increase the cost of wood heating.
    a. Increase home tax assessment value if home has wood burning units
    b. Insurance company fire insurance rates
        1. Urge insurance companies to adjust home fire insurance policy rates in proportion to whether wood heat is used and unit has been recently inspected
        2. Urge state insurance commissioners to require above action
4. Reduce prices of conventional and alternate fuels.
    a. Lifeline electricity rates
    b. Lower residential gas rates
    c. Lower residential oil rates
    d. Subsidies for solar energy use

C. Information/Technology Transfer

1. Disseminate efficiency information on burning units.
    a. By government agency
    b. By trade association
    c. By neutral research organization
2. Economics.
    a. Make public aware of true cost of wood heating
    b. Suggest to households that they limit fireplace usage to 10 occasions per season as a compromise between aesthetic use and avoiding heat loss
3. Health concern - make public aware of indoor air pollution consequencies of wood heating.
4. Safety Concern - make public aware of frequency of fires associated with home wood burning so as to discourage use.

5. Promote alternate radiant heat sources.
   - a. Promote natural gas fireplaces with greater visual simularity to wood fuel and therefore greater consumer appeal
   - b. Promote (clean) natural gas radiant space heaters
   - c. Promote passive solar usage
6. Promote wearing warm clothes indoors.
7. Heat key areas selectively.

III. OPERATING PROCEDURES FOR WOOD BURNING UNITS

A. Regulations

1. Technical chimney sweep program -- test emission rates on-site.
   - a. Opacity
   - b. Mass of particulates
   - c. Simple carbon measurement
   - d. Carbon monoxide measurement
2. Government authority to require cutbacks in wood usage during peak pollution periods.
   - a. Instantaneous - based on nephelometer or automatic particle monitor measurements
3. Sizing of Burning Units.
   - a. Government agencies require manufacturer to state on unit how much space can be heated with the unit for living space insulated to certain assumed levels
4. Moisture Content.
   - a. Require all commercial wood sales to include information on average moisture content
   - b. Limit free wood cutting on public lands to time periods (likely spring/summer) which maximize the probability that wood will be sufficiently dried before use

B. Market Incentives

1. Moisture content - government subsidizes a regional wood drying facility.

C. Information/Technology Transfer

1. Moisture Content.
    a. Educate wood users on the importance of moisture content with regards to emissions and efficiency
        1. Government publications
        2. Newspaper/television exposure
    b. Distribute plans for low cost solar wood dryers
    c. Distribute X free moisture meters to commercial wood distributors
2. Distribute information on avoiding creosote build-up/ minimizing emissions.
    a. Government employee activity (e.g., British Solid Fuel Advisory Service)
    b. Individual manufacturers distribute information to users
    c. Trade Association distribute information to users
    d. Generate media interest and media reporting
    e. Government agencies send latest information to manufacturers and distributors on how to minimize emissions
3. Burning Unit Sizing.
    a. Government agencies distribute information on importance of not over-sizing
    b. Trade Associations develop program for rating how much space can be heated with a given burning unit
4. Concerned Neighbor Approach.
    a. Concerned neighbors or neighborhood association members suggest to homeowners with smoky burning units how they could burn wood with less emissions

APPENDIX C

Ranking RWC Control Strategy Elements vs WANT Criteria

Table C1 shows the overall ranking of each of the seventy-five RWC control strategy elements (Appendix B) considered in this study versus the twelve WANT criteria defined in Section III of the text.

The total scores in the second column of Table C1 are documented in Table C2, which shows the individual scores assigned to each strategy element for each WANT criteria. The identification number in column three of Table C1 refers to the comprehensive listing of all seventy-five RWC control strategy elements, in Appendix B.

Note that when similar control strategy elements ranked closely in score they were combined in the Table C1 ranking. Thus, the seventy-five control strategy elements were combined into fifty-four ranking slots.

TABLE C1

Overall Ranking of Individual RWC Control Strategy Elements vs All WANT Criteria

Overall Rank	Total Score[1]	I.D. No.[2]	Description of Control Strategy Elements[2]
1	535	III.A.3	Government requires manufacturers to label stove as to space it can heat vs various house insulation levels.
2	504	II.A.1.a	Allow new stoves only in highly weatherized households.
3	487	I.A.1.a	Government required certification (vs emission standards) of new burning units.
4	480	II.A.1.b	Require all dwellings to be weatherized to cost effective level within 5 years or after resale.
5	476	II.A.1.d	Require utilities to help pay for weatherizing households.
6	471	II.A.1.c	Tax credits from government to offset some or all costs of weatherization.
7	469	I.A.1.b	Same as #3, but for existing units (retrofits).
8	468	III.C.3.a	Government distributes information on importance of not over sizing burning units.
9	465	III.C.3.b	Trade Association develop program for rating how much space can be heated by a burning unit (sizing).
10	459	I.B.1.a.4	Consumer subsidy to buy burning units cleaner than an established emission rate.
11	453	I.B.1.a.3	Same as #10, but variable subsidy, proportional to emissions rate.
12	447	I.B.1.c	Government sponsors $50,000 prize to designer of first burning unit which 1) costs less than or equal to $1000.00 and 2) emits less than or equal to 1 g/kg.

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[1] From Table C2

[2] From Appendix B

TABLE C1 (Cont.)

Overall Rank	Total Score[1]	I.D. No.[2]	Description of Control Strategy Elements[2]
13	437	I.C.2.c	Mandatory emissions testing by Trade Assoc.
	437	I.C.2.b	Mandatory emissions testing by Trade Assoc.
14	436	I.B.1.b	Tax disadvantage to companies proportional to the emissions levels of their burning units.
15	424	I.A.2	Government required rating of burning units for emissions to allow their sale at all.
16	422	III.A.4.a	Require commercial wood sales to include information on moisture content.
17	418	III.A.1.a	Chimney sweeps test household emissions.
	385	III.A.a.b,c,d	Chimeny sweeps test household emissions.
18	416	II.A.2.b	Stagger federal (USFS/BLM) wood cutting periods to help dry the wood - e.g., allow cutting in spring or summer.
	410	III.A.4.b	Stagger federal (USFS/BLM) wood cutting periods to help dry the wood - e.g., allow cutting in spring or summer.
19	415	II.A.4.b	Allow new burning unit only if efficiency standards.
20	407	II.A.4.a	Allow new burning unit only if it provides a "substantial net heat gain".
21	404	II.B.1.b	Government subsidizes weatherization in all areas.
22	403	II.C.2	Make public aware of the true cost of wood heating.
23	401	I.B.1.a.1	Consumer subsidy to buy cleaner (retrofit) new burning units.
	392	I.B.1.a.2	Consumer subsidy to buy cleaner (retrofit) new burning units.
24	395	I.C.1.a	Government provides free fully staffed testing facility.

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[1] From Table C2

[2] From Appendix B

TABLE C1 (Cont.)

Overall Rank	Total Score[1]	I.D. No.[2]	Description of Control Strategy Elements[2]
25	396	II.C.1.c	Disseminate information on burning unit efficiency by neutral organization, government, or Trade Association.
	387	II.C.1.a	
	380	II.C.1.b	
26	394	II.B.3.b	Lower residential rates for gas & oil.
	394	II.B.4.c	
27	383	III.C.1.b	Educate wood users as to moisture content effects on emissions and efficiency.
	390	III.C.1.a	Educate wood users as to moisture content effects on emissions and efficiency.
28	378	I.C.1.d	Government sponsors $50,000 prize for first test procedure system costing less or equal to $100.00.
29	364	I.C.3.a	Publish information on burning unit design considerations/research by government or Trade Association.
	358	I.C.3.b	Publish information on burning unit design considerations/research by government or Trade Association.
30	363	II.B.4	Lifeline electricity rates.
31	360	I.C.2.a	Voluntary Trade Association emissions rating program.
32	360	II.A.3.a	Emission Density Zone - allow only X burning units per $(\text{mile})^2$ based on pollutant dispersion capability.
33	359	I.C.1.b	Government gives tax credits on equipment or services for emissions testing of burning units.
34	357	I.C.1.c	Government funds development of standardized, simpler, and cheaper emission test procedures for burning units.

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[1] From Table C2

[2] From Appendix B

TABLE C1 (Cont.)

Overall Rank	Total Score[1]	I.D. No.[2]	Description of Control Strategy Elements[2]
35	359	II.A.2.b.1	USFS/BLM limits wood use to X cords/year based on air quality (or, to "X" cords per cutting permit).
	347	II.A.2.b.2	USFS/BLM limits wood use to X cords/year based on air quality (or, to "X" cords per cutting permit).
36	342	II.A.3.b	Emission Density Zone - allow only X cords burned per square mile, based on dispersion capability.
37	345	I.B.1.b.2.b	Government subsidy to manufacturers of burning units for pollution measuring equipment (or, for basic research).
	326	I.B.1.b.1.a	Government subsidy to manufacturers of burning units for pollution measuring equipment (or, for basic research).
38	341	III.C.2.a,d,e	Distribute information on avoiding creosote buildup/minimizing emissions by government or media (or Trade Association).
	331	III.C.2.b,c	Distribute information on avoiding creosote buildup/minimizing emissions by government or media (or Trade Association).
39	335	II.C.4	Make public aware of frequency of fires associated with RWC, to discourage use.
40	348	III.C.1.b	Distribute plans for solar wood driers.
41	315	III.C.1.c	Distribute free moisture meters to commercial wood distributors.
42	310	III.B.	Government subsidizes regional wood drying facility.
43	298	II.C.3	Make public aware of health concerns related to indoor air pollution from RWC.
44	293	II.C.6	Promote wearing warmer clothes indoors to reduce heating needs.

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[1] From Table C2

[2] From Appendix B

TABLE C1 (Cont.)

Overall Rank	Total Score[1]	I.D. No.[2]	Description of Control Strategy Elements[2]
45	285	II.C.5.a	Promote alternative radiant heat sources - e.g., natural gas fireplaces; passive solar; or gas heaters.
	283	II.C.5.c	
	275	II.C.5.b	
46	283	II.B.2.a	Increase wood prices to decrease RWC by subsidizing industry to use hogging residues which would firewood; or, by increasing USFS/BLM firewood cutting fees.
	271	II.B.2.b	
47	273	II.B.4.d	Subsidize solar energy as RWC alternative
48	264	II.C.7	Promote spot heating of key areas in house (e.g., heat lamp in bathroom).
49	304	II.B.1.a	Government subsidizes weatherization but only in areas with severe pollution potential.
50	238	III.A.2.a	RWC cutbacks during air pollution episode.
	273	III.A.2.b	
51	252	II.A.2.a	Require USFS/BLM EIS to assess air quality effects of their firewood releases.
52	235	III.C.4	Concerned neighbor approach - neighbors tell others how to reduce RWC emissions.
53	234	II.B.3.b	Increase cost of RWC by encouraging State Insurance Commission or private carriers to raise home fire insurance rates for RWC households; or, raise property tax assessments.
	225	II.B.3.a	
54	211	II.C.2	Suggest households limit annual fireplace usage to 10 occasions to reduce heat loss and emissions.

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[1] From Table C2

[2] From Appendix B

TABLE C2
Keppner-Tregoe Scores for Individual RWC Control Strategy Elements vs All WANT Criteria

I. Burning Unit Design

WANT Criteria[1]	Weight Factor	A. Regulations		B. Market Incentives			C. Technology Transfer		
		I.A.1	I.A.2	I.B.1.a	I.B.1.b	I.B.1.c	I.C.1	I.C.2	I.C.3
1. Reduce RWC emissions/household	13	8,8	6	7,7,8,8	(4,4) 8	9	4,3,3,3	4,6,6	3,3
2. Reduce no. of RWC households	13	3,3	3	2,2,2,2	(1,1) 3	3	3,3,3,3	4,3,3	3,3
3. Widely applicable/effective	10	8,7	8	6,5,5,5	(5,5) 6	6	6,5,5,6	3,8,8	2,2
4. Maximize public acceptance	9	8,8	7	7,7,7,7	(5,5) 8	6	5,5,6,6	9,7,7	9,9
5. Discourage worst appliances	9	9,9	6	2,2,7,8	(6,5) 8	5	6,5,5,6	5,7,7	4,3
6. Minimize consumer cost	6	3,3	4	10,10,10,10	(7,8),6	7	7,7,7,7	4,3,3	8,8
7. Use proven technology	5	6,5	6	6,6,6,6	(3,4),6	3	6,6,3,3	6,6,6	9,9
8. Minimize circumvention	4	8,8	6	5,5,5,5	(5,5),5	6	6,6,6,6	5,7,7	3,3
9. Maximize agency feasibility	3	1,1	1	5,6,6,5	(3,4),5	5	5,6,6,5	1,2,2	7,8
10. Encourage innovative technology	2	7,6	6	6,5,7,7	(9,8),5	10	9,7,8,10	5,7,7	5,5
11. Minimize free market interference	2	6,6	8	2,2,2,2	(3,2),1	7	7,6,7,7	6,8,8	6,6
12. Promote conservation and renewable resources	1	2,1	1	2,2,1,1	(2,2),2	2	2,1,1,2	1,2,2	1,1

WANT Criteria Scores:

	I.A.1	I.A.2	I.B.1.a	I.B.1.b	I.B.1.c	I.C.1	I.C.2	I.C.3
1	487	424	401	326	447	395	360	
2	469		392	345		359	437	
3			453	436		357	437	
4			459			378		
5								

[1] All MUST Criteria have been met.

II. Reduce Wood Usage

WANT[1] Criteria	Weight Factor	Regulations				Market Incentives				Technology Transfer					
		II.A.1	II.A.2	II.A.3	II.A.4	II.B.1	II.B.2	II.B.3	II.B.4	II.C.1	II.C.2	II.C.3	II.C.4	II.C.5	II.C.6
1. Reduce RWC emissions/ household	13	9,9,8,8	2,(4,3,6	8,3	1,3	5,8	4,3	1,(1,1)	3,3,3,1	4,4,4	5,3	2	4	2,2,2	4,3
2. Reduce no. of RWC households	13	8,9,4,4	4,(8,8,7	8,7	6,8	3,3	7,5	7,(5,5)	7,8,8,5	3,3,3	6,4	6	6	6,6,6	4,4
3. Widely applicable/ effective	10	8,9,6,6	2,(7,7,6	7,6	9,4	5,6	5,4	5,(4,4)	5,5,5,3	2,2,2	3,1	2	2	3,2,1	3,2
4. Maximize public acceptance	9	3,1,5,6	5,(3,3,4	3,3	3,3	3,7	0,5	0,(4,4)	6,8,8,5	8,7,8	8,3	6	6	5,5,5	5,5
5. Discourage worst appliances	9	7,7,5,5	1,(5,5,6	8,7	6,5	5,6	7,3	3,(3,3)	5,5,5,3	6,5,6	6,1	4	4	3,3,3	3,3
6. Minimize consumer cost	6	0,0,10,1	8,(7,7,8	7,7	7,7	0,0	3,6	5,(5,5)	0,10,10,6	8,8,8	8,8	7	8	8,8,8	8,8
7. Use proven technology	5	7,8,8,8	8,(0,0,0	0,0	8,8	8,8	0,0	0,(0,0)	0,0,0,0	8,8	0,0	0	0	0,0,0	0,0
8. Minimize circumvention	4	6,3,8,8	6,(2,2,3	2,2	2,2	1,2	1,2	1,(2,2)	6,6,6,5	4,4,4	4,1	3	4	4,4,3	3,3
9. Maximize agency feasibility	3	1,1,5,6	3,(1,1,4	1,1	1,1	5,6	1,2	1,(2,2)	0,0,0,5	7,8,7	8,3	5	5	3,3,3	3,3
10. Encourage innovative technology	2	4,4,4,4	3,(1,1,4	1,1	7,7	4,4	1,1	1,(1,1)	0,0,0,8	6,6,6	1,2	1	1	1,1,0	3,1
11. Minimize free market interference	2	2,6,2,2	6,(2,3,4	2,3	2,3	3,2	0,1	2,(3,3)	0,0,0,3	8,8,8	6,4	6	6	2,2,3	3,3
12. Promote conservation	1	7,8,6,5	1,(2,1,1	2,1	6,7	5,6	0,0	1,(1,1)	0,0,0,6	6,5,6	2,1	1	2	0,0,6	6,4

WANT Criteria Scores:

	II.A.1	II.A.2	II.A.3	II.A.4	II.B.1	II.B.2	II.B.3	II.B.4	II.C.1	II.C.2	II.C.3	II.C.4	II.C.5	II.C.6
1	504	252	360	407	304	283	225	363	387	403	290	335	285	293
2	480	359	342	415	404	271	234	394	300	211			275	264
3	471	347					234	394	396				263	
4	476	416						273						
5														

[1] All MUST Criteria have been met.

* Multiple numbers indicate individual scores for subheading under each control strategy as listed in Appendix B. For example, for WANT criteria 1 (8,8) indicates score of 8 for Strategy IA1a and a score of 8 for Strategy IA1b. Similarly, total scores of 487 and 469 listed at bottom of column are for IA1a and IA1b, respectively.

TABLE C2 (Cont.)

III. Operating Procedures

WANT[1] Criteria	Weight Factor	Regulations				Market	Technology Transfer			
		III.A.1	III.A.2	III.A.3	III.A.4	III.B.1	III.C.1	III.C.2	III.C.3	III.C.4
1. Reduce RWC emissions/household	13	5,5,5,5	1	8	4,6	5	(5,5),4,3	5,5,5,5,5	7,7	3
2. Reduce no. of RWC households	13	4,4,4,4	4	5	3,7	3	(3,3),3,3	3,3,3,3,3	5,5	4
3. Widely applicable/effective	10	8,6,6,6	8	7	7,6	3	(4,3),2,2	3,2,2,3,3	4,3	1
4. Maximize public acceptance	9	3,3,3,3	6	8	8,4	3	(7,7),6,5	6,6,6,6,6	8,8	5
5. Discourage worst appliances	9	5,5,5,5	0	6	6,6	5	(5,6),5,5	5,5,5,5,5	5,6	1
6. Minimize consumer cost	6	7,7,7,7	6	8	6,8	5	(8,7)8,8	8,8,8,8,8	8,8	9
7. Use proven technology	5	8,7,7,7	0	8	7,0	7	(7,7),5,7	0,0,0,0,0	8,8	0
8. Minimize circumvention	4	7,6,6,6	3	8	7,3	5	(3,3),4,1	4,4,4,4,4	4,3	0
9. Maximize agency feasibility	3	5,4,4,4	4	5	4,4	2	(8,8),8,7	7,7,7,7,7	7,8	2
10. Encourage innovative technology	2	4,4,4,4	3	7	3,4	3	(3,3),6,3	5,5,5,5,5	6,6	3
11. Minimize free market interference	2	6,6,6,6	4	8	8,5	3	(6,6),6,6	6,6,6,6,6	7,7	6
12. Promote conservation and renewable resources	1	4,3,3,3	0	5	2,1	1	(1,1),1,1	1,1,1,1,1	4,3	2
WANT Criteria scores:										
1		418	273	535	422	310	390	341	468	235
2		385			410		383	331	465	
3		385					343	331		
4		385					315	341		
5								341		

[1] All MUST criteria have been met.

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* Multiple numbers indicate individual scores for subheading under each control strategy as listed in Appendix B. For example, for WANT criteria 1 (8,8) indicates score of 8 for Strategy IA1a and a score of 8 for Strategy IA1b. Similarly, total scores of 487 and 469 listed at bottom of column are for IA1a and IA1b, respectively.

APPENDIX D

Estimated RWC Emissions Reduction Potential of Control Strategy Approaches

This Appendix explains the information and assumptions used in attempting to quantify the potential reduction in air pollutant emissions which might be achievable by implementing the control strategy **approaches described in Section V of this report. The reader of** this documentation will soon appreciate that it contains many significant assumptions, some of them arbitrary "best estimates", because hard information was unavailable.

The sections of this Appendix are numbered to correspond to Section V in the report. Several long additional sections are interspersed in this appendix which address "Key Topics", such as: 1) emission reductions achievable by advanced design stoves; 2) basis for selecting 33% tax credit; 3) burn rate effects for stoves/furnaces, and; 4) reducing stove charge size.

The following quantitative assumptions are referred to in a number of the cases documented in this Appendix.

> The average particulate emission rate of the current mix of wood stoves in use is assumed to be 40 lbs per ton of wood burned (20 g/kg); and for fireplaces is assumed to be 20 lbs/T (10 g/kg); assuming 1.75 tons of wood/cord.[1]
>
> This is based on emissions tests conducted by the Oregon Department of Environmental Quality, using the "Oregon Method 7"[29] test procedure[1j] and on airshed modeling and chemical mass balance analyses which indicate that these emission factor values yield predicted concentrations which are in close agreement with measured RWC impacts.[1n, 27] Sanborn of the Vermont Air Pollution Control Program also estimates that the 20 g/kg emission factor is a good average value for wood stoves,[28] based on similar test

methods. This method captures more condensible organics than the EPA Method 5 procedure with back-half catch, because it utilizes an additional filter between the 3rd and 4th impingers in EPA's Method 5 apparatus. Other researchers have commonly reported stove emission in the 1 - 97 g/kg range, but the average of the 19 tests conducted in Task 5 of this study was 28 g/kg. These differences are likely due to different sampling procedures, burn rates, and some test procedures not including start-up emissions.

A. Improved Burning Unit Design

This section reviews the potential for reducing RWC particulate emissions through

1. Improved design of new stoves offered for sale including analysis of the following strategy approaches.
   a. Testing of wood stoves and certification of compliance with an established emission limit as a prerequisite for allowed sales.
   b. Testing/certification as a prerequisite of stove sales plus financial incentive (33% tax credit) to buy the cleaner stoves.
   c. Testing/certification as a basis for mandatory labelling which specifies stove efficiency and emissions performance.
   d. Testing/certification as a basis for mandatory labelling, plus 33% tax credit.

2. Modifications of installed stoves, including:
   a. Air inlet modifications
   b. Insertion of firebrick in stove box.
   c. Fans to improve heat transfer.
   d. Add-on particulate control devices:
      1. Steel wool mesh filter
      2. Catalytic afterburner

3. Improved design or add-on devices for fireplaces.
   a. Underfire air.
   b. Electrostatic precipitator
   c. Glass doors.

Key Topic: Emissions Reductions Achievable by Advanced Design Stoves

New stoves of special design have achieved particulate emissions rates as low as 1-4 g/kg of wood burned, as illustrated by four different designs described here.

Refractory-lined, Water-Cooled, Turbulent Air Furance

The first system is a refractory-lined, water-cooled, turbulent air furnace based on the design of Professor Richard Hill. A furnace based on the Hill design, the Hampton-Jetstream, was tested in 1980 by the Oregon Department of Environmental Quality and was found to emit 3.4 and 3.9 grams particulate/kilogram wood in two separate tests.[1j]

The principles which are thought to be responsible for this unit's clean burning characteristics are: 1) the unit burns very hot, enabling more complete **combustion,** yet still maintains high thermal efficiency by extracting heat from the stack by a water-cooling system; 2) turbulent air introduced improves air-fuel mixing in the combustion zone allowing more complete combustion, and; 3) the water-cooling system also is used to keep cool the area storing wood which currently is not burning, which reduces "wood volatilization" prior to burning, and allows a steadier fuel-air mixture to be maintained.

The unit has an overall efficiency (thermal and combustion efficiency) of 79%, as tested by the manufacturer. However, it has one major drawback - an installed cost in the range of $5000 to $7000.[24]

The units costs about $3500 without auxiliary plumbing. However, in order to either tie into or construct a water-to-air heat exchange system costs on the order of $1500 to $3500, raising the system cost into the $5000 to $7000 range. Despite the high price which limits this unit's applicability for most households, the low emission rate which it achieves shows the potential for emission reductions.

Ceramic Stove

The second unit of interest is a ceramic stove tested under Task 5 of this contract. Test results showed that the unit emitted at 1 and 2 g/kg in two different tests.[20]

The chief drawback of this unit is its relatively low heat transfer efficiency, which results in an average overall efficiency of about 50%, and its inability to allow an operator to control its burn rate. Once fired, the unit burns wood in a hot and rapid manner, which is not consistent with many wood user's desire for a slow and steady radiant heat source.[24] However, the fact that this unit burns very clean suggests that other units also can achieve this emission level. For this unit, the application of some heat-exchanging mechanism between the stove box and house chimney exit could substantially increase the thermal efficiency, by storing some of the heat for release at a more convenient rate.

Gasifying Stove

The third unit of interest is a gasifying stove, the Jotul 201, to be marketed by Jotul beginning in April 1982.[24] This unit has been tested for efficiency and CO emissions but not yet for particulates. However, the efficiency and CO results suggest this unit also should have low emissions of other pollutants. The gasifying stove is able to more completely burn the volatilized wood gases by channelling them to an upper combustion chamber.

In tests at "low-output", which normally is the most difficult way to burn with low emissions, the unit had a six-hour average CO stack gas concentrations of .05% of CO.[30] This compares to CO levels of .2 and .4% for the ceramic stove cited above during runs with particulate emission factors of 1 and 2 g/kg. For "medium-output" and "high-output", the model 201 had average CO concentrations of .28% and .69%.[30] The very low CO levels at "low and medium-output" are of greatest interest since people tend to operate their stoves at low to medium burn rates. However, even though this CO data suggests the unit will operate at a low burn rate with low particulate emissions, the correlation between CO and particulate is uncertain. (During Task 5 of this study a correlation of .80 was found for CO and particulate concentrations but the data are limited.) This means that some stoves with low CO emissions may still have high particulate emissions, and thus particulate testing is needed to know the particulate emission rate for this stove with confidence.

Overall efficiency for the 3 Jøtal tests conducted by the manufacturer was between 75 and 78.5% and combustion efficiency for the three runs ranged between 93.3 and 96.3%[30], which indicates that relatively complete combustion was occurring. Until particulate emissions are actually measured, the real emission rate cannot be known, but it seems likely to be in the 2 and 10 g/kg range.

Catalytic Afterburner

Lastly, wood burning stoves with catalytic afterburners are available which hold potential for reducing emissions by additionally combusting some of the stack gas exhaust that would otherwise be emitted as particulate. Although particulate emission testing on several catalytic stoves has not shown any of these units to have significantly reduced emission characteristics, research by several authors on efficiency suggests that catalysts can help burn a significant (undefined) portion of the tars, vapors, soot, and creosote that could otherwise escape up the stack.

For example, Shelton has reported[16] overall efficiency increases of 20% from about 50 to 60% net efficiency, and noted large temperture differentials between locations above and below the catalyst. However, merely installing a catalyst "wafer", through which stack air must pass in the upper part of a stove's firebox does not guarantee increased combustion efficiency or significantly reduced emissions. To optimize complete combustion, the requirements of time, temperature, good air-fuel ratios, and good mixing must be met. To aid catalyst combustion, secondary air likely is needed, but it may need to be preheated to avoid quenching combustion in the catalyst zone. The amount of secondary air supplied must be appropriate for the combustible content of the stack gas, and there must be sufficient turbulence to promote good mixing of the introduced secondary air and the exhaust gases. Catalyst stoves which have balanced and optimized these different requirements in a specific design likely will achieve the best performance. To this point, no specific catalyst stoves have been shown to have substantially reduced particulate emission characteristics, using either the EPA Method 5, the Oregon Method 7, or comparable emissions testing procedure. However, future optimization of these requirements appears possible in a manner that could reduce emissions by 75%, or more. At that point, the remaining problem will be the length of catalyst life, and how to ensure catalyst replacement at appropriate times (likely 2 years or less).

Based on this review of advanced stove/furnace designs, the following key assumptions are made, for purposes of estimating the potential emissions reductions achievable in the future from strategy approaches which encourage the development and installation of wood stoves designed to have minimum emissions:

Assumption: Wood burning stoves will be available by January 1984 at a cost of $1200 or less, with particulate emissions of 5 g/kg or less - i.e., 75% less than the current estimated average emissions rate of 20 g/kg.

This date is selected because it is two years forward from this assessment of stove technology, allowing time for a number of manufacturers to follow up on designing units employing principles from the advanced designs described above. Regarding the cost estimate, the last three units discussed all cost less than $1000. Numerous manufacturers have agreed in personal conversations that if a burning unit is developed with high (70-80%) efficiency and low emission characteristics which costs less than $1000, it likely will be able to claim a large share of the market for new units. Thus even with inflation and design research costs factored into stove/furnace prices, the above assumption seems reasonable. This assumption forms a key basis for estimates described below of the potential emissions reductions achievable by four strategy approaches which assist and promote the development and installation of burning units with much lower air pollutant emissions rates.

. . . .

1. Improved Design of New Stoves

RWC emission reductions achievable were estimated for four strategy approaches designed to promote development and installation of cleaner burning wood stoves/furnaces. The following four strategy approaches were analyzed:

a. Testing/certification as prerequisite for sale

b. Testing/certification as prerequisite for sale, plus a 33% tax credit for purchasing a certified unit

c. Testing/certification as basis for mandatory labelling of efficiency and emission performance.

d. Testing/certification/mandatory labelling, plus a 33% tax credit for purchasing a certified unit.

The following key assumptions were used for purposes of the analysis:

- Baseline RWC emissions and wood fuel use (status quo, if no strategy was implemented) for wood stoves/furnaces for 1980-2000 would be as described in Figure D1 and Table D1, which show the best estimate, long-term trend for Portland, Oregon from Task 3 of this study.
- The % coverage* assumed for the four strategy approaches listed above, i.e., the % of new stove/ furnace purchases which would be cleaner (certified) burning units, is 60%, 90%, 20%, and 40%, respectively.
- Certified stoves/furnaces which would emit 80% less particulate than existing units (i.e., 4.5 g/kg), would be commercially available by January 1984 at a cost of $1200.
- Stove/furnace life (ave.) is 10 years, i.e., 10% of existing units are replaced each year.

The four strategies analyzed in this subsection reduce RWC emissions from wood stoves and furnaces only. Table D2 summarizes the stove/furnace wood usage (cords/year) assumed for purposes of this analysis, and the degree to which each of the four strategies would result in the use of cleaner (certified) burning units. This is translated in Table D3 into the emissions reductions available over time with each strategy approach.

In Table D2 the wood usage assumed is the best estimate of long-term (1980-2000) wood usage projected for Portland, Oregon in Task 3. These wood usage projections are shown in columns 2 and 3 of Table D2 as the annual increase and cumulative total cords/year, respectively. In columns 4 and 5 wood usage information is transformed into index values using 1980 as a base year. That is, the 150,000 cords/year burned in stoves/furnaces in 1980 is given an index value of 100. All other wood usage data in columns 2 and 3 then is translated into equivalent index values in columns 4 and 5. Since these index values directly reflect RWC in stoves/furnaces, they also reflect the relative number of stoves/furnaces in use, provided we assume that the average wood usage (cords/year) in stoves/furnaces remains constant throughout the analysis period (1974-2000). This assumption allows the index values derived to represent relative wood usage to also represent the relative number of stoves/furnaces in use in which this wood is burned. Accordingly, index values also can be used to calculate the relative number of certified and non-certified stoves/furnaces in use in any year.

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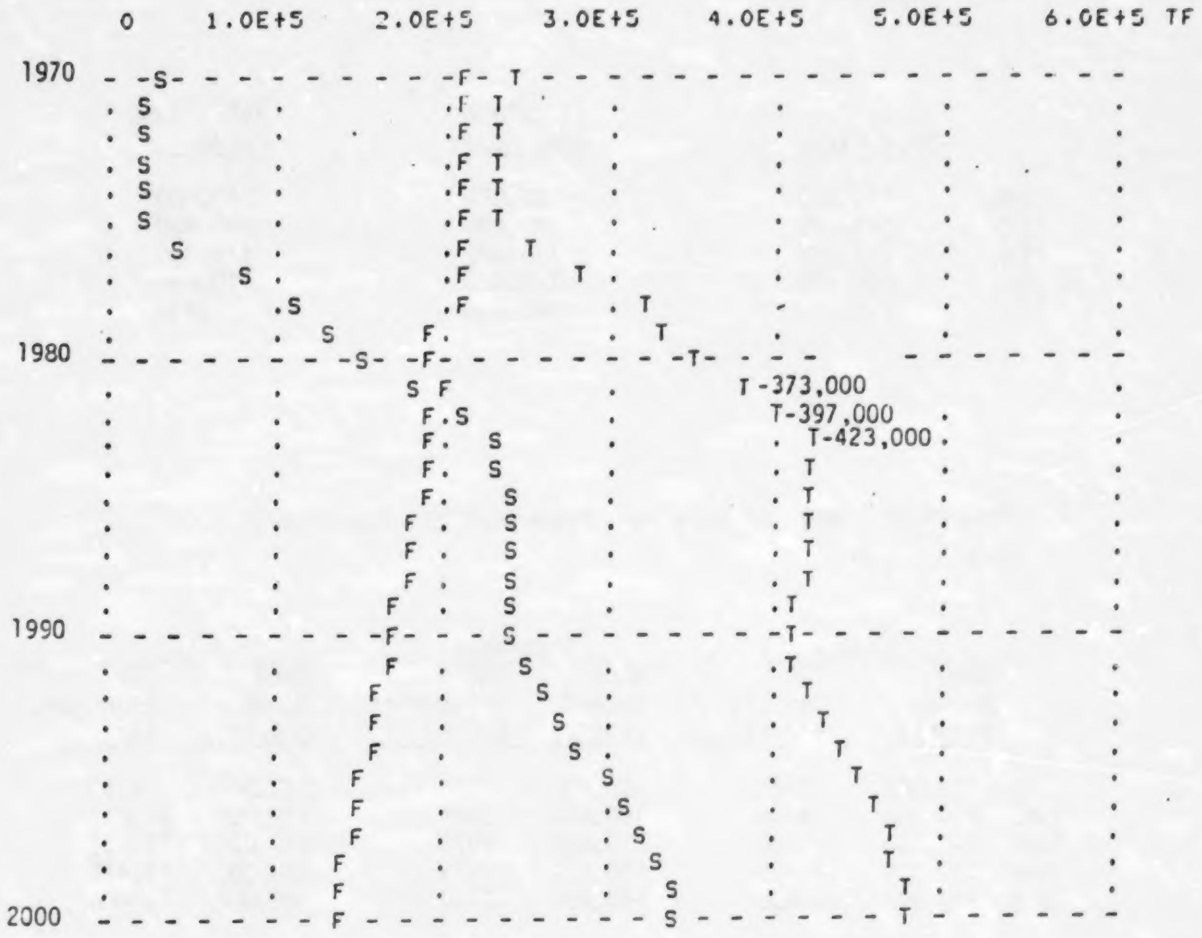
* % coverage refers to the percent of purchased units which have emission factors of 5 g/kg or less.

FIGURE D1

Base Case 1970 to 2000 Projection
for
Portland Metropolitan Areas for Wood Usage



Source: Table 5 page 54 Task 3 report.

Stove and Furnace Wood Usage (S), Fireplace Wood Usage (F), and Total Wood Usage (T).

TABLE D1

Assumed 1980-2000 Baseline RWC Wood Fuel Use and RWC Emissions

A. **Best Estimate Projection of Residential Wood Usage in Portland for 1980 to 2000**[31]

	Stove/Furnace Wood Usage	Fireplace Wood Usage	Total Wood Usage
1980	150,000	190,000	340,000
1985	240,000	190,000	430,000
1990	240,000	170,000	410,000
1995	300,000	150,000	450,000
2000	340,000	140,000	480,000

B. Projected Change in Emissions From Portland Residential Wood Burning[31]

	Stoves		Fireplaces		Total	
	Wood Burned (Cd/Yr)	TSP Emissions* (T/Yr)	Wood Burned (Cd/Yr)	TSP Emissions* (T/Yr)	Wood Burns (Cd/Yr)	TSP Emissions* (T/Yr)
1980	150,000	5925	190,000	3325	340,000	9250
1985	240,000	9480	190,000	3325	430,000	12,805
1990	240,000	9480	170,000	2975	410,000	12,455
1995	300,000	11,850	150,000	2625	450,000	14,475
2000	340,000	13,430	140,000	2450	480,000	15,880

* Assuming 1.75 tons wood/cord; fireplace and stove TSP emission factors of 20 and 45 lbs.ton[20], respectively. Emission factors are assumed to remain constant.

TABLE D2

Index Values for Certified and Non-Certified Wood Stove/Furnace Use at Different Strategy Effectiveness Rates

Column:	2	3	4	5	6	7	8	9	10	11
	Wood Usage*		Stove/Furnace RWC Index Values							
Year	(Cords/Year)		Baseline Total		100% Strategy Effectiveness			60% Strategy Effectiveness		
					Non-Certified		Certified	Non-Certified		Certified
	New Annual	Cumulative	New Annual	Cumulative	New	10 yr old		New	10 yr old	
1973	-0-	18,750	-0-	12.5	-0-	-	-0-	-0-	-	-0-
4	-0-	18,750	-0-	12.5	-0-	-	-0-	-0-	-	-0-
5	-0-	18,750	-0-	12.5	-0-	-	-0-	-0-	-	-0-
6	21,875	40,625	14.6	27.1	14.6	-	-0-	14.6	-	-0-
7	40,625	81,250	27.1	54.2	27.1	-	-0-	27.1	-	-0-
8	28,125	109,375	18.8	73.0	18.8	-	-0-	18.8	-	-0-
9	21,875	131,250	14.6	87.6	14.6	-	-0-	14.6	-	-0-
1980	18,750	150,000	12.5	100.0	12.5	-	-0-	12.5	-	-0-
1	31,250	181,250	20.8	120.8	20.8	-	-0-	20.8	-	-0-
2	28,125	209,375	18.8	139.6	18.8	-	-0-	18.8	-	-0-
3	21,875	231,250	14.6	154.2	14.6	12.5	-0-	14.6	12.5	-0-
1984	-0-	231,250	-0-	154.2	-0-	12.5	1.25	5.8	12.0	0.5
5	9,375	240,625	6.2	160.4	-0-	11.25	8.6	-0-	11.5	4.9
6	-0-	240,625	-0-	160.4	-0-	24.7	11.1	2.5	25.4	6.4
7	-0-	240,625	-0-	160.4	-0-	49.3	16.0	-0-	51.0	9.5
8	-0-	240,625	-0-	160.4	-0-	63.2	22.3	-0-	66.7	13.5
9	-0-	240,625	-0-	160.4	-0-	71.5	29.5	-0-	77.3	18.1
1990	-0-	240,625	-0-	160.4	-0-	76.9	37.2	-0-	85.2	23.2
1	9,375	250,000	6.2	166.7	-0-	90.0	52.4	-0-	100.9	33.0
2	9,375	259,375	6.2	172.9	-0-	99.8	68.6	2.5	113.7	45.5
3	9,375	268,750	6.2	179.1	-0-	104.4	85.2	2.5	121.5	56.5
4	12,500	281,250	8.4	187.5	-0-	93.96	103.0	2.5	120.0	68.7
1995	18,750	300,000	12.5	200.0	-0-	84.6	124.0	3.4	112.8	83.0
6	9,750	309,750	6.5	206.5	-0-	76.1	138.1	5.0	108.5	93.4
7	9,000	318,750	6.0	212.5	-0-	68.5	151.0	2.6	102.0	103.1
8	12,500	331,250	8.4	220.9	-0-	61.6	165.6	2.4	95.9	113.9
9	9,375	340,625	6.2	227.1	-0-	55.4	177.3	3.4	90.1	123.0
2000	-0-	340,625	-0-	227.1	-0-	49.9	182.3	2.5	84.7	128.1

TABLE D2 (Cont.)

Column:	12	13	14	15	16	17	18	19	20
Year	Stove/Furnace RWC Index Values								
	90% Strategy Effectiveness			20% Strategy Effectiveness			40% Strategy Effectiveness		
	Non-Certified		Certified	Non-Certified		Certified	Non-Certified		Certified
	New	10 yr old		New	10 yr old		New	10 yr old	
1973	-0-	-	-0-	-0-	-	-0-	-0-	-	-0-
4	-0-	-	-0-	-0-	-	-0-	-0-	-	-0-
5	-0-	-	-0-	-0-	-	-0-	-0-	-	-0-
6	14.6	-	-0-	14.6	-	-0-	14.6	-	-0-
7	27.1	-	-0-	27.1	-	-0-	27.1	-	-0-
8	18.8	-	-0-	18.8	-	-0-	18.8	-	-0-
9	14.6	-	-0-	14.6	-	-0-	14.6	-	-0-
1980	12.5	-	-0-	12.5	-	-0-	12.5	-	-0-
1	20.8	-	-0-	20.8	-	-0-	20.8	-	-0-
2	18.8	-	-0-	18.8	-	-0-	18.8	-	-0-
3	14.6	12.5	-0-	14.6	12.5	-0-	14.6	12.5	-0-
1984	1.46	11.4	1.0	11.7	12.25	0.25	8.8	12.0	0.5
5	-0-	10.4	7.5	-0-	12.1	1.7	-0-	11.5	3.4
6	0.62	24.1	9.7	5.0	26.5	2.2	3.7	25.6	4.4
7	-0-	49.0	14.1	-0-	53.1	3.3	-0-	51.7	6.5
8	-0-	63.4	19.8	-0-	70.8	4.7	-0-	68.4	9.2
9	-0-	72.3	26.3	-0-	84.0	6.4	-0-	80.3	12.4
1990	-0-	78.3	33.3	-0-	94.8	8.3	-0-	89.6	16.0
1	-0-	92.1	47.8	-0-	113.7	11.8	-0-	106.8	22.8
2	0.62	102.6	62.6	5.0	130.2	15.6	3.7	121.3	30.1
3	0.62	108.0	77.9	5.0	142.2	19.7	3.7	131.1	37.8
4	0.62	99.8	94.5	5.0	151.1	24.4	3.7	134.7	46.6
1995	0.84	90.8	114.0	6.7	148.1	29.9	5.0	129.3	56.8
6	1.25	83.3	127.4	10.0	150.1	34.2	7.5	127.8	64.5
7	0.65	75.6	139.6	5.2	147.1	38.3	3.9	122.7	71.8
8	0.60	69.0	153.4	4.8	144.2	42.9	3.6	117.8	79.9
9	0.84	62.8	164.7	6.7	141.3	47.0	5.0	113.1	86.9
2000	0.62	57.2	169.8	5.0	138.5	49.8	3.7	108.6	91.2

For example (Table D2), in 1992 wood usage was 259,375 cords/year, or 1.729 times as much as in 1980. This translates to a 1992 wood usage index value of 172.9 relative to 1980 wood usage. The increase of 9,375 cords/year in 1992 over the previous year is 0.0625 times as much wood usage as in 1980, for an index value of 6.25 (Column 4) representing new annual wood usage. This increase in wood usage represented by the index value of 6.25 also can be assumed to represent an increase in the relative number of stoves/furnaces, assuming constant average wood use per stove/furnace. For a strategy with 60% "coverage" - i.e., 60% of the purchasers of new stoves buy cleaner (certified) units - the number of new certified units purchased that year can be represented by an index value of 3.72 (.6 x 6.2); and the number of new non-certified units (Column 9) by 2.5 (.4 x 6.2).

To calculate index values representing the number of certified and non-certified stoves/furnaces in use in any given year, for any strategy effectiveness assumed, the following three expressions were used (the expressions shown are for the 60% coverage case, i.e., Columns 9 - 11).

- To calculate index value for new non-certified stoves/furnaces for year y (Column 9):

  $(\text{Column } 9)y = (1.0 - \text{SC Frac})(\text{Column 4 value})_{y-1}$

  (SC = strategy coverage)

- To calculate index value for non-certified stoves/furnaces 10 years old for year y (Column 10):

  $(\text{Column } 10)y = (\text{Col } 10)_{y-1} - (\text{Col } 10)_{y-1}\ (.1)(\text{SC Frac}) + (\text{Col } 4)_{6-10}$

- To calculate index value for certified stoves/furnaces for year y (Column 11):

  $(\text{Column } 11)y = (\text{Col } 11)_{y-1} + (\text{Col } 4)y\ (\text{SC Frac}) + (\text{Col } 10)_y\ (.1)(\text{SC Frac})$

  Where:

  SC Frac = the fraction of new/replacement stoves purchased which are certified - i.e., which emit at 5 g/kg or less.

Column 11 index values represent the number of certified stoves/furnaces in use. Column 5 index values represent the total stoves/furnaces in use. Thus, Column 11/Column 5 is the fraction of all stoves/furnaces in use which are certified. This certification fraction (Cert. Frac.) can be used to calculate the RWC emissions reductions for any given year due to the use of certified stoves, as follows:

$$\text{Emissions Reduction}(\%) = \text{Cert.Frac.}(0.75)(100)$$

where 0.75 represents the assumption that certified stoves/furnaces emit 75% less particulate then existing units. That is, certified units will average 5 g/kg vs existing emissions levels of approximately 20 g/kg estimated by DEQ.[27]

Table D2 contains index values developed for strategy approaches with coverage levels of 100%, 60%, 90%, 20%, and 40%. The last four represent the four strategy approaches listed at the beginning of this subsection. **Table D3 summarizes the potential stove/furnace particulate emissions reductions for all five cases, assuming strategies are implemented in 1984. Since stoves/furnaces are assumed to account for about 70% of total RWC emissions by the mid-1980's, multiplying the values in Table D3 by 0.7 affords the potential reduction in overall RWC emissions (Table 7).**

Table D3 indicates that the most **effective of the four strategy approaches, (testing/certification as a prerequisite for sale,** plus a 33% tax credit, which was assumed to be 90% effective) reduces RWC particulate emissions from stoves/furnaces by only 3.5% after two years (by 1985). However, its benefits accumulate such that it reduces these emissions by almost 16% by 1990 and by 56% by the year 2000.

The second most effective of the four strategy approaches analyzed, testing/certification as a prerequisite for sale, assumed to be 60% effective, resulted in almost 11% less emissions by 1990 and 42% less by the year 2000.

The strategy approach assumed to be 40% effective, testing/certification as a basis for mandatory labelling, plus a 33% tax credit, resulted in almost 8% less RWC emissions by 1990, and 30% less by the year 2000.

The least (20%) effective of the four strategies achieved a 4% reduction in RWC emissions by 1990, and 17.5% by 2000.

TABLE D3

Particulate Emissions Reduction (%) Achievable at Five Strategy Coverage Levels

YEAR	Strategy Coverage Levels (% Clean Stoves Installed of Total New Stoves Installed)				
	100%	60%	90%	20%	40%
1984	0.6	0.3	0.5	0.1	0.3
1985	4.0	2.3	3.5	0.8	1.6
6					
7					
8					
9					
1990	17.4	10.8	15.6	3.8	7.5
1					
2					
3					
4					
1995	46.5	31.1	42.8	11.3	21.3
6					
7					
8					
9					
2000	60.2	42.3	56.1	16.4	30.1

Emissions Reduction (%) = (Cert. Frac.)(.75)(100)

Example Calculation (1985; 90% Coverage):

Emissions Reduction (%) = (Cert. Frac.)(.75)(100)

Emission Reduction (%) 7.49/160.4 (.75)(100) = 3.5%

Key Topic: Basis for Selecting 33% Tax Credit

In Portland, Oregon particulate emissions from RWC are now projected to exceed **total industrial particulate emissions (tons/year)** by the mid-1980s.[11] Pollution control tax credits are available in Oregon to industries which must install particulate control devices, for up to 50% of the installation costs.[32] Tax credit levels for wood burning equipment can be estimated using industrial particulate control costs.

A recent study addressed growth management issues for the Portland airshed.[33] It estimated industry must pay about $10,000 in pollution control costs per ton of particulate to obtain emissions offset to locate in the Portland urban area ($5.00 per lb. of TSP). Up to 50% of such costs would be eligible for tax credit under Oregon laws and regulations.[32] The Oregon Department of Environmental Quality estimates that average TSP emission factors are 40 lb/ton (20 g/kg) for stoves and 20 lb/ton (10 g/kg) for fireplaces.

A household which burns 2 cords/year in a wood stove (2 X 1.75 tons/cord = 3.5 tons/year) would emit 140 lbs of **TSP** per year (40 x 3.5 = 140). If these emissions were to be counterbalanced by industrial emission reductions, it would cost either industry or the state through its tax credit program a combined total of $700. If a residential tax credit program were set up in a manner comparable to how the industry program operates in Oregon, then the state could subsidize **up to $350 of costs if these emissions were totally controlled, or** about $263.00 if the emissions were reduced by 75% ($700 x .75 x .5 = $262.50). This significant level of economic incentive to purchase cleaner units could stimulate development of cleaner units even if their manufacturing costs were several hundred dollars more per unit than "dirtier units".

Another approach to setting a tax credit level might be to assume that development of such cleaner stove/furnace designs would add to the costs of producing a unit by, say 50%. Then whatever the price of the unit turned out to be, an appropriate level of tax credit to offset development costs, would be 33% (50% cost increase is equivalent to 33% of final total costs). Thirty-three percent of the assumed 1984 competitive cost ($1200) of advanced design stoves/furnaces is $1200 x .33 = $400. This value was selected for purposes of this analysis.

. . . .

2. Modifications of Installed Stoves/Furnaces

a. Air Inlet Modifications

Barnett reported research findings[11] on the effect on emissions of a simple change in air flow pattern. A thin-walled convection wood stove was tested. Instead of introducing air as normal from both a front and back draft hole, the front hole was blocked off, and a tube was extended from the back draft hole horizontally to the back center. Air supply was thus introduced between the logs near the center of the stove. Particulate emissions were found to decrease about 50% as a result of this simple modification. This finding suggests that manufacturers of stoves might be able to reduce emissions by 50% with inexpensive modifications to the air supply inlet construction, perhaps for $20 per stove or less in additional construction costs.

Since optimum design is not known for certain, in order for manufacturers to ascertain whether the addition (of an air supply tube into the back center of the firebox) actually reduces emissions, some simple emission measurement technique is needed that could give manufacturers inexpensive feedback on emissions. Without such feedback widespread introduction of this or similar modifications may not occur at all.

As a retrofit strategy it is unreasonable to believe that more than 1 or 2% of stove owners would ever be sufficiently concerned about air emissions to voluntarily make such a modification. Retrofits would be more likely if significant fuel savings resulted. A strategy of requiring that stove owners modify their existing stoves by changing the air supply configuration does not appear to be practical because no single "modification kit" could apply to all stoves and there could be serious safety problems if novice stove owners were to alter their stove designs. Thus no emission reduction credit can be claimed for this "retrofit" strategy.

b. Insertion of Firebrick in Stovebox

Some have theorized that possible flame quenching near firebox walls could be reduced by lining the stove box with refractory or firebrick.

Firebrick insertion into the stove box has been theorized by some as a means to increasing combustion zone temperature and combustion efficiency and thereby reduce emissions. Insufficient combustion zone temperature can mean less than complete combustion, because the spontaneous ignition temperature of volatilized wood gases ranges from 670 to 1200° F.[13]

However, research on this technique as applied to a thin-walled stove by Barnett[11] did not show any significant emission reduction. Accordingly, no emission reduction can be expected from this practice.

c. Heat Transfer Improvements (Fans)

The application of fans or blowers to existing units for the purpose of heat recovery from stack gases can theoretically increase thermal efficiency, thereby reducing the amount of wood burned. Assuming combustion efficiency remains constant, if heat transfer efficiency increases, then gross efficiency increases by the same proportion. For example, if modifications to exisitng stoves could increase heat transfer and increase efficiency from 50 to 55%, (assuming combustion efficiency remained constant) 9% less wood (55-50)/55 would need to be burned to produce the same amount of heat and theoretically 9% less emissions would be produced.

Research by Shelton[14] on one fireplace-stove showed that application of a larger blower with roughly 570% more cfm (900 vs 134) than the existing blower increased energy efficiency by margins not exceeding 5%. This suggests that increasing blower capacity on a unit designed to have forced air for heat transfer is not likely to reduce emissions by much more than about 5%.

Barnett[15], in work comparing the conditions of 1) no forced-air heat exchanging and 2) application of a blower, found about a 5% increase in thermal (heat transfer) efficiency resulting from adding the blower.

For the homeowner who might be convinced to add some fan behind or near their wood stove to increase heat transfer, the thermal efficiency improvement (and theoretical emission reduction based on reduced wood burning) is likely limited to less than 5%.

Even if 20% of homeowners were to install a fan near their stove or increase the blower capacity on stoves with blowers, if the improvement in thermal and overall efficiency is limited to 5% as discussed, then only a 1% reduction in wood burning might occur. Thus the practical potential for this strategy as a retrofit strategy is considered to be negligible, or 0-1%.

d. Add-on Particulate Control Devices

Regarding particulate emission reduction achievable for stoves by add-on devices only two sets of tests have been done. The first was by the Oregon Department of Environmental Quality[11] and the second was part of Task 5[20] of this study. In the 1980 tests sponsored by DEQ, a steel wool mesh filter (cost $150) inserted into the stack was found to reduce total particulate emissions by 60% (limited two test comparison).

In work by OMNI and Del Green Associates in 1981 under Task 5 of this contract, the emission factor in a test with the steel wool mesh filter was actually higher (limited two test comparison).

In another set of OMNI/Del Green tests one add-on catalytic afterburner was tested. It also was inserted into the stack about six inches above the stove box. The test with the add-on unit showed slightly lower emissions, by about 10%, but this differential should be considered negligible in light of experimental error.

Given other uncertainties about how long these add-on control devices might perform, and whether clogging may ultimately **occur, it is uncertain that any significant add-on particulate control device will be available in the marketplace in the next five years, where significant device is defined as a unit that can reduce emissions on a continued basis by 20% yet still cost less than $150.**

In order to withstand public opposition to government requirements for a retrofit device that reduced emissions from wood stoves, any such device would have to have proven significant effectiveness, maintain effectiveness over time, overcome all potential safety problems, yet still be reasonably inexpeensive (i.e., less **than $200). Because of the lack of data indicating such devices to be currently available, the emission reduction potential from such a strategy is considered to be negligible (0-1%) for the near future.**

3. Improved Design of Add-on Devices for Fireplaces

a. Underfire Air

The effect of underfire air on fireplace emissions has been tested to a limited degree by PEDCo-Environmental[17] (January 1979). Of 18 source tests conducted for fireplaces, one of the tests measured emissions from a fireplace with underfire air. This test can be compared to four other tests with similar burn rates and same wood type, as shown in Table D4 below. This comparison indicates about a 40% emission reduction was achieved by application of underfire air to a fireplace.

TABLE D4

PEDCo Fireplace Source Tests: Underfire Air and Electrostatic Precipitator Comparison

Burning Unit	Wood Type	Burn Rate (kg/Hour)	TSP Emission Factor (g/kg)	Control Measure
Fireplace	Dry Pine	11.4	9.5	Underfire air
Fireplace	Dry Pine	8.2	16.6	None
Fireplace	Dry Pine	11.5	15.3	None
Fireplace	Dry Pine	10.1	16.7	None
Fireplace	Dry Pine	15.2	8.7	Electrostatic Precipitator

Although this one particular test with underfire air showed a 40% (41.4%) emission reduction, the burn rates in these tests are perhaps twice as high as normal burn rates. Thus, this same percentage reduction might not be achievable at lower burn rates.

The underfire air unit tested cost about $90. This low cost for the sizable emission reduction that was achieved in at least this one case, argues that more research is warranted on this low cost retrofit measure, especially over the range of burn rates commonly used by individuals. Given uncertainties about whether these results apply at lower burn rates, the technical potential for emission reductions by this technique is estimated at 0 to 40% for an individual unit, based on this limited test information .

This strategy would have to be applicable as a retrofit strategy in order to have significant effect. However, there is a far greater chance that a retrofit device such as this could be developed and commercialized for fireplaces than for stoves since one or two designs likely could fit most fireplaces. Potential safety problems such as air outlet hole plugging would need to be overcome.

The retrofit device would necessarily include a blower **system which would require use of electric power. Even if** the units were given free to dwellings with fireplaces, probably only about 50% of households would utilize the units. Practical emission reduction potential would thus appear to be in the 20% range for fireplace units to which this technology is applied.

This strategy is applicable primarily to new fireplace installations. Fireplaces in the Portland area account for about 30% of RWC emissions and thus that value is used for this calculation of benefits. By 2000, new fireplaces (post 1984) may account for about one-third of all fireplace emissions. If underfire air technology were applied to all new fireplaces after 1984, the 10% of all RWC emissions from post-1984 fireplaces (.3 X .333 = .10) would be estimated to be reduced by 20% by 2000 which equates to a reduction in all RWC emissions of 2% by 2000 (.10 X .2 - .02) but only about half that amount by 1990.

b. Electrostatic Precipitator

It has been hypothesized by some that an electrostatic precipitator could control emissions despite incomplete combustion. Although feasible, the high cost (about $1400) for the emission reduction achievable (perhaps 50%) make this strategy unlikely as a widespread solution for individual fireplaces (and also stoves by extension).

In one of the PEDCo tests[17] cited above (Table D4) a 45% **(46.3%)** emission reduction was found to occur when a commercially available ESP was applied. The "Smog-Hog" used by PEDCo in their tests was reported to cost $850 in 1977, and is estimated to cost $1400 installed in 1982.

Even assuming optimistically that such a 45% reduction could be achieved for all burn rates, applications, etc. this very high cost makes this strategy impractical for individual units. For apartment buildings where multiple flues may be tied together to have a common exhaust flow, economies of scale may be able to reduce costs per fireplace to more reasonable levels.

c. Glass Doors

Can the application of glass doors alter the combustion process in a fireplace such that greater combustion efficiency and lesser emissions result? Although the available data again is limited[14], it appears that 1) operating a fireplace with glass doors shut dramatically reduces gross efficiencies during the burning period because the doors reduce heat transfer, and 2) covering the fireplace opening with either glass doors or other devices only during the night time burndown/smoulder phase can cut house heat loss by an undetermined percentage. Regarding combustion efficiency and emissions, no evidence was found in the literature that glass doors as normally installed can either increase combustion efficiency or reduce emissions.

B. Reducing Wood Usage

This section reviews the following strategy approaches for reducing RWC emissions by reducing wood usage:

1. Reducing home heating requirements
    - a. Weatherization
    - b. Reducing stove charge size and burn rate
2. Improving wood fuel quality
    - a. Selection of wood with higher heating value
    - b. Moisture content control (seasoning)
        1. Fireplaces - moisture content effects
        2. Stoves/furnaces - moisture content effects
3. Direct restrictions on wood use
    - a. Episode controls
    - b. Emission density zoning

Before discussing the strategy approaches in this section a general discussion is presented of the relationship between burn rate and particulate emission, because it is relevant to several of the strategies evaluated hereafter.

Key Topic: Burn Rate Effects - Stoves/Furnaces

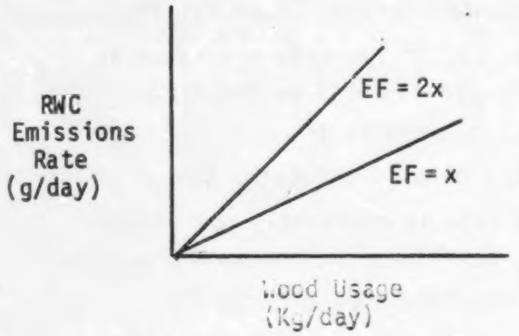
Total RWC particulate emissions from stoves/furnaces (kg/day) are a function of the amount of wood burned (lbs/hr, kg/day, etc.) and the emission factor of the woodburning unit, usually expressed as grams of particulate emitted per kilogram of wood burned (g/kg). This idea is illustrated schematically in Figure D2(a). Both of these determinants of RWC emissions - wood usage and emission factor can be a function of the rate at which the wood is burned in the stove/furnace (kg/hr).

A given amount of wood burned should provide the same amount of heat whether it is burned slowly or at a more rapid rate, provided that the combustion and thermal efficiencies of the burning unit remain constant. This will often not be the case, especially over a wide range of burning rates, for several reasons. Hotter fires (higher burn rates) may lose more heat via exhaust gases, reducing thermal efficiency. Slower burn rates may not maintain sufficient temperature in the firebox for as complete combustion of volatiles, reducing combustion efficiency (and increasing emissions). The stove operator also may believe that at lower burn rates his heat output is not adequate and add more wood.

For purposes of this analysis wood usage is assumed to be a direct function of burn rate (Figure D2(b)). However, the emission factor is assumed to vary with burn rate as shown in Figure D2(c), based on research described below. This relationship is important in estimating the potential emissions reductions achievable by several of the strategy approaches examined here.

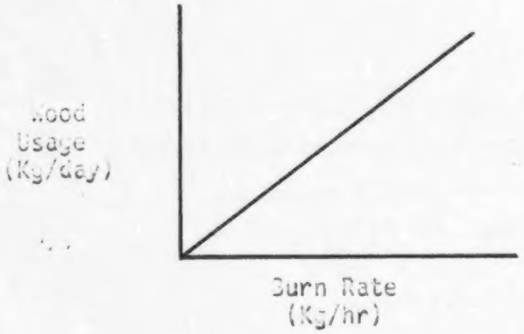
FIGURE D2

General Relationships Assumed
Between
Key Wood Burning Unit Variables

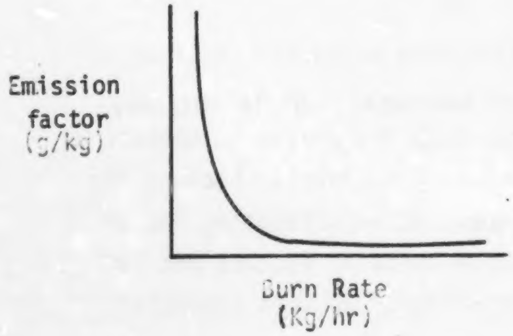


where:
EF = Emission factor (g/kg)

A. RWC (particulate) emissions is the product of wood usage and emission factor.



B. Wood Usage varies directly with burn rate (combustion and thermal efficiencies remain constant hours of burning remain constant).



C. Emission factor decreases as burn rate increases.

Stove/furnace emissions test results reviewed below clearly show that as burn rate increases, emissions factors decrease. This reflects higher combustion efficiencies at higher firebox temperatures. However, whether or not total emissions over time is greater or less at the higher burn rates depends upon whether the higher wood usage at higher burn rates offsets the lower emissions factor. That is, if doubling the burn rate cuts the emission factor in half, but twice as much wood is burned, the total emissions per day will be the same.

We have assumed for purposes of this analysis that wood usage will vary linearly with burn rate (Figure D2(b)). However, the variation of emissions factor with burn rate is apparently not linear (Figure D2(c), Figure D3). The latter, non-linear relationship must be examined more closely, because it has important implications for several RWC strategy approaches, and for such practices as operating stoves/furnaces in an "airtight" or banked mode.

Review of Existing Research

Butcher (1979) published findings that particulate emission factors from airtight wood stoves are inversely proportional to burn rates and directly proportional to fuel load in the stove box.[13] He derived the following equation to describe this relationship:

$$\underset{(g/kg)}{\text{Emission Factor}} = 10.73\ (m/q) + 1.18$$

where, m = initial fuel load in firebox (kg)

q = combustion rate (10,000 Btu/hr)

Other researchers[1i,1j,1m,1o,20] also have noted how emission factor increase dramatically as burn rate decreases. While this may seem to suggest that stoves/furnaces should be encouraged to operate at higher rates, the situation is not necessarily so simple, because the higher wood usage at higher burn rates could be an offsetting factor.

The quantitative relationship between emission factors and burn rates is not understood completely at this time. In work conducted in this study (Task 5), when the relationship between emission factors and burn rates was evaluated for a set of 14 tests on wood burning stoves, an alternate equation was found to describe the burn rate vs emission factor relationship with a -.92 correlation coefficient. The equation derived from these results was:

$$\underset{(g/kg)}{\text{Emission Factor}} = 156\ e^{-0.84x} = 156/e^{.84x}$$

where, x = burn rate in kg/hr

An equation of similar form, but with different coefficients, was derived by the Oregon Department of Environmental Quality based on similar tests.[1j]

Figure D3 illustrates these two different representations of the relationship between burn rate and emission factor, i.e., the Butcher and Del Green Associates equations, respectively. The data plotted in Figure D3 are shown in Table D5. This data was derived using the burn rates in Column 1 in both equations 1 and 2 above to calculate an emission factor. To assure consistent treatment of the different burn rate terms in equations 1 and 2, a conversion factor of 4258 Btu/lb of wood burned was used. For Butcher's equation, a fuel load of 6.2 kg was assumed (m = 6.2), because this produced emissions and emission rates of similar magnitude to those from the Del Green equation. A different "m" value could be chosen and the relative change in emission factor for a given burn rate change would be about the same. The "m" value of 6.2 was chosen for this example because then the two emission factor curves in Figure D3 are in close proximity and it is easier to perceive their similarity of slope.

Figure D3 shows that the two equations are similar in curve shape, and similar in position on the graph when Butcher's m = 13. Table D5 shows that for a burning rate decrease of 0.5 lb/hr, over a range of burning rates (Column 1), the two equations afford different changes in relative emission factors (Columns 2 and 3). Butcher's equation indicates that the increase in emission factor for a 0.5 lb/hr decrease in burning rate will be greater for lower initial burn rates (Column 2). The Del Green Associates equation indicates that each 0.5 lb/hr decrease in burn rate will increase the emission factor by 21.5% (Column 3).

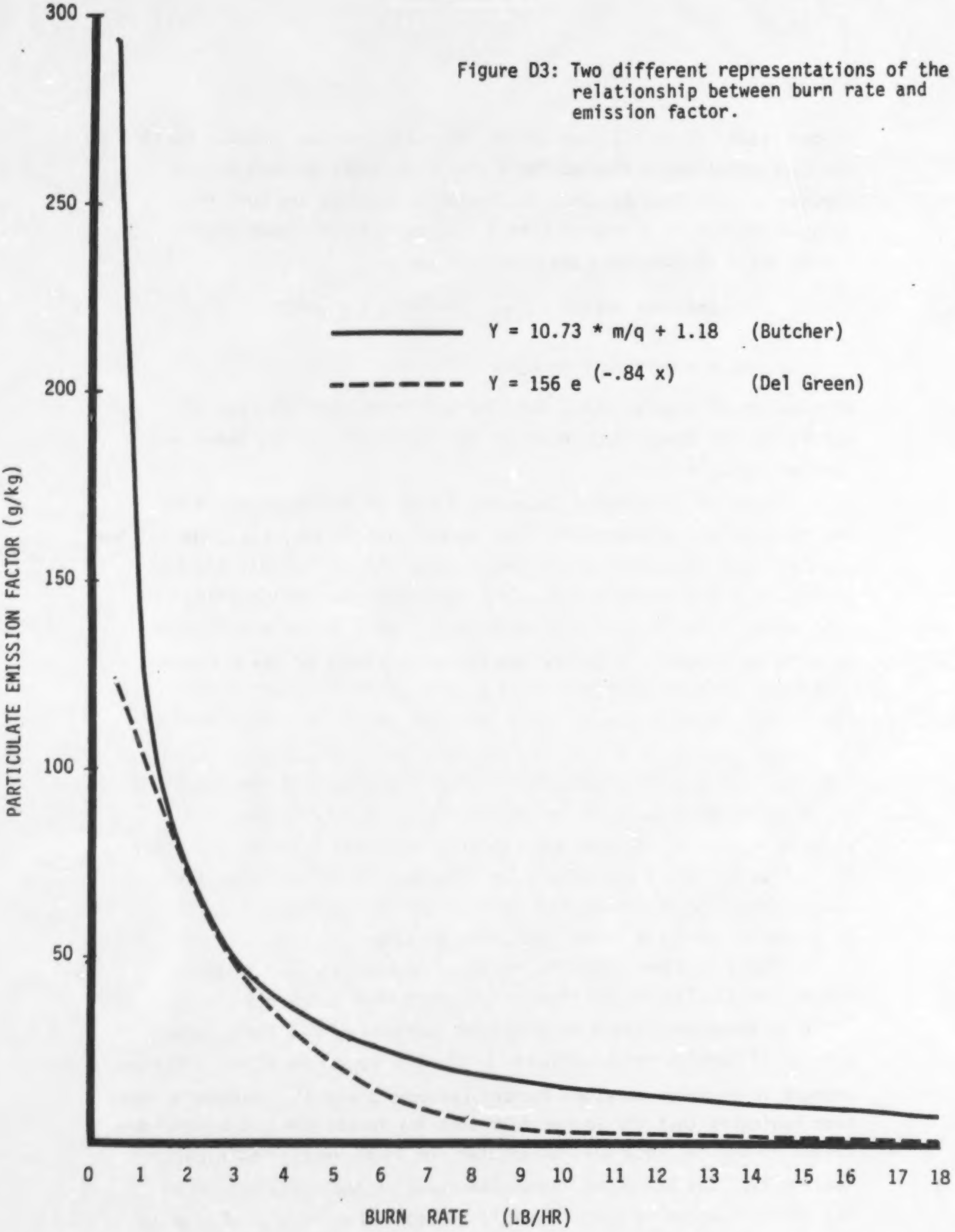


Figure D3: Two different representations of the relationship between burn rate and emission factor.

TABLE D5

Emission Factors Calculated for a Range of Burn Rates Using the Butcher and Del Green Equations

Burn Rate (lb/hr)	Emission Factor (g/kg) Using Two Equations	
	Butcher $10.73(m/q) + 1.18$*	Del Green $156/e^{.84x}$
0.5	297	129
1.0	149	107
2.0	75	73
2.5	60	60
3.0	50	50
3.5	44	41
4.0	38	34
4.5	34	28
5.0	31	23
5.5	28	19
6.0	26	16
8.0	20	7
10.0	16	3.5
14.0	12	.75
16.0	10	.35

* "m" assumed to equal 6.2 kg.

The matrices in Figures D4 and D5 show the relative increase or decrease in emission rate for a much wider array of burn rate changes, using the Butcher and Del Green Associates equations, respectively.

In Table D6 the relative amount of wood burned (Column 4) is governed by the burn rate. Butcher's equation indicates that the total emissions per day will be the same in all cases (Column 5), because lower wood usage at lower burn rates will be almost exactly offset by higher emission rates (assuming operators continue to charge the same volume of wood per loading). The Del Green Associates equation indicates that total emissions per day would be greater or lesser depending upon the initial burn rate, with reduced total emissions per day achieved only for burn rate decreases below about 2.5 lb/hr (Column 6). Table D7 shows how the total wood burned, heat output, and particulate emissions would vary with burning rate for a ten-hour burn period, where emissions are calculated using both the Butcher and Del Green equations. Total wood usage (Column 2) over ten-hour ranges from 15 to 55 lbs, governed by burn rate (Column 1).

Heat output (Btu) similarly ranges from 6.4 to 23.6 10^3 Btu/hr (Column 3). This range should cover the space heating output required for most homes, since Day reports that typical wood stove burn rates produce about 8-15,000 Btu/hr.[24]

Columns 4 and 5 indicate how total (10 hr.) particulate emissions vary for each of the burn rates in Column 1, using both the Butcher and Del Green equations. Total emissions are essentially the same in all cases (Column 4) using Butcher's equation. Using the Del Green equation, total emissions peak at a burn rate of about 2.5 lb/hr (Column 5). This is probably a typical burn rate for households in climates comparable to Portland and Seattle. Barnett's field studies in upstate New York for climate with about 5000 heating degree days per year (comparable to Portland and Seattle) found stove burn rates most commonly in the 2.0 to 2.5 lb/hr range.[1p] Columns 6 and 7 show how dramatically emissions per unit of heat output increase as burn rate decreases.

FIGURE D4

Relative Increase or Decrease in Stove Emissions Factors (%)
Estimated for an Array of Burn Rate Changes
Using the Del Green Equation

Final Burn Rate lb/hr Initial Burn Rate lb/hr	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1.5	-0-	-17	-32	-44	-53	-61	-68	-74	-78	-82
2.0	21	-0-	-17	-32	-44	-53	-61	-68	-74	-78
2.5	46	21	-0-	-17	-32	-44	-53	-61	-68	-74
3.0	77	46	21	-0-	-17	-32	-44	-53	-61	-68
3.5	114	77	46	21	-0-	-17	-32	-44	-53	-61
4.0	159	114	77	46	21	-0-	-17	-32	-44	-53
4.5	214	159	114	77	46	21	-0-	-17	-32	-44
5.0	280	214	159	114	77	46	21	-0-	-17	-32
5.5	359	280	214	159	114	77	46	21	-0-	-17
6.0	456	359	280	214	159	114	77	46	21	-0-

FIGURE D5

Relative Increase or Decrease in Stove Emissions Factors (%)
Estimated for an Array of Burn Rate Changes
Using the Butcher Equation

Final Burn Rate lb/hr Initial Burn Rate lb/hr	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1.5	-0-	-25	-40	-49	-56	-62	-66	-69	-72	-74
2.0	33	-0-	-20	-33	-42	-49	-55	-59	-63	-66
2.5	65	25	-0-	-16	-28	-37	-44	-49	-53	-57
3.0	98	49	20	-0-	-14	-24	-33	-39	-44	-49
3.5	130	73	39	16	-0-	-12	-22	-29	-35	-41
4.0	161	97	58	32	14	-0-	-11	-19	-26	-32
4.5	193	121	77	48	28	12	-0-	-10	-18	-24
5.0	224	144	96	64	41	24	11	-0-	- 9	-16
5.5	255	168	115	80	55	36	21	10	-0-	8
6.0	286	191	134	95	68	48	32	19	9	-0-

TABLE D6

Emissions Per Day Resulting From Changes in Emission Factors
Caused By Changes in Burn Rate
Calculated Using Butcher and Del Green

Burn Rate Change (lbs/hr)	Ratio of Emission Factors @ Lower Burn Rate (g/kg) / @ Higher Burn Rate (g/kg)		Ratio of Daily Wood Burned @ Lower Burn Rate (lbs/day) / @ Higher Burn Rate (lbs/day)	Ratio of Total Emissions per Day @ Lower Burn Rate (kg/day) / @ Higher Burn Rate (kg/day)	
	Butcher	Del Green	Butcher or Del Green	Butcher	Del Green
1.5 to 2.0	1.3280	1.210	0.75	.996	.908
2.0 to 2.5	1.2451	1.210	0.80	.996	.968
2.5 to 3.0	1.1953	1.210	0.833	.996	1.008
3.0 to 3.5	1.1622	1.210	0.857	.996	1.037
3.5 to 4.0	1.1384	1.210	0.875	.996	1.059
4.0 to 4.5	1.1207	1.210	0.889	.996	1.076
4.5 to 5.0	1.1068	1.210	0.900	.996	1.089
5.0 to 5.5	1.0958	1.210	0.909	.996	1.100
5.5 to 6.0	1.0867	1.210	0.916	.996	1.108

Assumes: 4285 Btu/lb of wood burned.

TABLE D7

Total Wood Burned, Heat, and Emissions Output During a Ten-Hour Burn at Different Burn Rates

Burn Rate (lbs/hr)	Wood Burned (lbs)	Heat Output[1] 10^4 Btu/hr	Particulate Emissions		Emissions/Unit of Heat	
			Kg/10 hours		Kg/10^4 Btu	
			Butcher	Del Green	Butcher	Del Green
1.5	15	0.643	.678	.599	1.055	.933
2.0	20	0.857	.681	.660	.795	.771
2.5	25	1.071	.684	.682	.638	.637
3.0	30	1.286	.686	.677	.534	.527
3.5	35	1.500	.653	.459	.459	.435
4.0	40	1.714	.692	.616	.404	.360
4.5	45	1.928	.694	.573	.360	.297
5.0	50	2.143	.697	.526	.325	.246
5.5	55	2.357	.700	.479	.297	.203

[1] Assumes 4285 Btu/lb of wood burned.

Burning Briskly During Initial Stages of a Fire

An additional relevant characteristic of stove particulate emissions is that about 50% of the total emissions are produced in the first one-sixth (17%) of the burn. This finding was first made by Butcher in 1977[35] and confirmed by O.D.E.Q. testing conducted in 1980 and 1981.[1j] This phenonema can be best understood in the context of the phases of wood burning which occur. During wood combustion, the processes which occur are:

- water is vaporized
- volatiles are vaporized/combusted
- char is combusted

During the initial stages of a fire, the relatively cool firebox temperatures (heating the stove's thermal mass takes time) and the presence of steam can retard complete combustion. Since the greatest amount of volatiles are produced in the initial stages of a fire, a relatively greater oxygen supply is needed to enable close to complete combustion to occur. This explains the basis for the commonly cited recommendation of "burning briskly in the first 20 to 30 minutes" of a new fire or after a large charge of wood is added to the firebox.

Although there is no direct estimate in the literature of the reduction in emissions which is achievable by "burning briskly in the first half hour", such an estimate can be generated based on the burn rate discussion presented above. For example, for an individual stove, if the operator "burns briskly" at three times the normal burn rate during the first half hour of a four hour burn, he will be reducing the emissions rate expected in the first one-eighth (30/240 minutes) of the firing period by 33%. This practice can be estimated to reduce emissions by about 25%, provided the total amount of wood burned remains constant, as shown below:

- 50% of emissions occur in first 40 minutes (one-sixth of 240 minutes)
- Brisk burning occurs for 75% of that time period (30/40 minutes)
- Brisk burning is assumed to be three times the normal burn rate, which implies a 67% emission rate reduction during that time period; and a 200% increase in amount of wood burned during these 30 minutes
- **Emissions are thus assumed to be reduced by 25% for the entire period, assuming the total amount of wood burned is the same.** .50 x .75 x .67 = .25

Thus for an individual stove, it is estimated that burning briskly at three times the normal rate during the first one-eighth of the fire could reduce emissions by about 25%, so long as the wood burned per fire does not change. However, tripling burn rate during the first one-eighth of the normal burn length would result in a 25% increase in overall wood usage, unless the burn rate during the remaining seven-eighths of the normal burn length is reduced to 75% of normal. Two cases are considered in Table D8 in which the burn rate during the remaining 7/8 of the fire: 1) is at the "normal" rate so that overall wood use increases 25%, and; 2) is reduced to 75% of normal.

In Case #1 the temporary decrease in emission rate achieved by burning briskly during the first 30 minutes, is offset by the fact that maintaining the normal burn rate during the rest of the fire increases overall wood use by 25%. The net result is no decrease in emission compared to the Base Case.

In Case #2, after burning briskly as in Case #1, the wood use (burn rate) during the rest of the fire is kept below "normal" such that the total amount of wood burned over the course of the fire is the same as the Base Case. The net result in 17.9% less emissions compared to the Base Case.

Assuming most households would not cut normal wood use back by a full 25% during the final 7/8 of the fire, a more realistic assumption could average the results of Cases #1 and #2 for purposes of this analysis, it was assumed most probable that relative emissions (last column above) would be reduced by about 10%. It was further assumed that no

TABLE D8

Scheme for Comparing Relative Emissions Associated with Two Overall Wood Use Rates

Portion of The Fire	Relative Amt. Wood Burned (lb)	Emission Rate[1] (Units/lb of Wood burned)	Relative Emission[1] (Units/Fire)
A. Base Case ("normal" burn rate)			
First 30 minutes	3	5x	15x
Next 10 minutes	1	5x	5x
Final 200 minutes	20	x	20x
TOTAL	24		40x
B. Burn Briskly Case #1[2]			
First 30 minutes	9	5/3x	15x
Next 10 minutes	1	5x	5x
Final 200 minutes	20	x	20x
TOTAL	30		40x
C. Burn Briskly Case #2[3]			
First 30 minutes	9	5/3x	15x
Next 10 minutes	.71	5x	3.55x
Final 200 minutes	14.29	x	14.24x
TOTAL	24		32.84x

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[1] Assumes 50% of emissions occur during first 40 minutes of a 240 minute fire.

[2] "Normal" burn rate tripled during first 30 minutes; overall wood used increased 25%.

[3] Normal burn rate tripled during first 30 minutes; overall wood use rate "normal".

more than 1/3 of RWC households could be persuaded to thus burn briskly and reduce normal wood use during the rest of the fire. This results in most probable emissions reductions of 3.3% from burning briskly only in the fire with moderate wood use thereafter.

Fireplace - Burn Rate Effects

No basis was found in the literature for estimating what emission rate change will occur when fireplace burning rates are altered. Thus no emission rate change can be attributed to any strategy which might focus on fireplace burn rates.

Burn Rate Conclusions

Several major conclusions emerge from this examination of burn rate, which affect estimates of the emissions reductions potentially achievable from strategy approaches which involve burn rate changes.

First, different research results show significantly different descriptions of the basic relationship between burn rate and emissions factor. The source and significance of these differences can only be illuminated by further research. Existing data is limited, i.e., published emissions test results address only selected stoves from among the variety in use. Variations in test conditions and methods could explain some of the differences in observed results. Much more extensive testing under standardized conditions is needed to clarify the quantitative relationships between key combustion variables such as burn rate and emissions rate.

Second, if increases in burn rate which decrease the associated emission factor are simply accompanied by comparable increases in wood usage, total emissions over time should remain about the same. Accordingly, we assume here that these two factors offset each other, unless stated otherwise, as explained below. Butcher's equation 1) indicates this cancelling effect would occur for all burn rates examined here (Table D6, Column 5) when initial fuel load (m) is held constant. The Del Green equation suggests this happens for burn rates around 2.5 lb/hour, but that improved (reduced) total emissions can occur at lower burn rates, and worse (higher) total emissions can occur at higher burn rates (Table D6, Column 6).

Third, based on the evidence at hand we cannot determine whether the Butcher or Del Green equation is more appropriate for use here in estimating potential emissions reductions (if any) from burn rate increases. However, we note that both equations afford the same or approximately the same results in the "most common" range of burn rates (2-3 lbs/hr; Table D6, Columns 5 and 6, entries 2-4). This result is essentially that which the Butcher equation postulates for the entire range of burn rates - namely, that burn rate increases result in no net change in emissions/day, because increased wood usage compensates for lower emission rate. Thus, it will be our assumption that no reductions in net emissions/day occur for burn rate increases at least in or near the "most common" range of 3-4 lb/hr burn rate.

Fourth, Table D6, Columns 6 and 7, shows that particulate emissions per Btu of heat output can be dramatically lower at higher burn rates. However, some mechanism for storing much of the heat produced at high burn rates, and releasing it over time, appears necessary to take advantage of higher burn rates as an emissions reduction strategy. This is because the higher burn rates produce more Btu/hr (Table D7, Column 3) than the 8-15,000 Btu/hr considered typical.[24] At burn rates above 15,000 Btu/hr (about 4.0 lbs/hr at 4285 Btu/hr assumed here), many households might find the heat output uncomfortably warm, and their wood comsumption rate uncomfortably high, if such high burn rates were to be maintained continuously. Without some heat storage (mechanism), the only way to obtain a comfortable heat output with significantly less emissions is to alternate periods of high burn rates with periods of no burning, or very low burning rates. This would not provide the even flow of heat sought by stove operators.

Examples of wood stoves which include a heat storage principle include 1) stoves lined with refractory, like the ceramic stove, which radiate heat stored in the refractory material after the fire inside has died down, and; 2) Richard Hill's refractory lined, water-cooled, turbulent air furnace, which uses water as well as refractory material for heat storage and circulation.

Fifth, we have so far used Butcher's equation by assuming constant fuel loads (m). This is consistent with typical operator procedures. For example, Shelton has noted that "many, if not most, operators use about the same size fuel load under all conditions and use the combustion air control to regulate power output".[1k] However, Butcher's equation with q held constant also implies that emissions rates can be reduced by charging smaller loads of wood (smaller m in Butcher's equation) while maintaining a constant burn rate, or rate of heat output (q, Btu/hr). This provides a basis for postulating emissions reductions from inducing operators to charge smaller loads of wood while maintaining their normal hourly burn rate (q), i.e., to charge the stove more frequently with smaller loads (m), while burning the same amount of wood over time.

This would be less convenient. It is perhaps most palatable and likely to occur for smaller stove sizes where the "normal" load for a larger stove would overfill the smaller stove's firebox. This is relevant to the strategy approach of down-sizing stoves to allow "hotter fires" without making a room uncomfortably warm. A "hotter fire" should increase combustion efficiency, lowering emissions. However, if the fire is made hotter by increasing burn rate, increased wood use can cancel any benefits of lowered emission rates, according to Butcher's equation; and for the Del Green equation for the "most common" burn rates.

Alternatively by charging smaller loads (m), more frequently but maintaining the small hourly burn rate (q), emissions should decrease in proportion to decreases in average charge size (m). Especially in a smaller stove, this could result in higher firebox temperatures (better combustion efficiency; lower emission rates) for several reasons. First, there is less stove mass to heat, so the same wood usage should be able to keep it hotter. Second, smaller charges may mean less unburned wood in the stove at any time. Unburned wood can act as a heat sink, lowering firebox temperatures.

. . . .

1. Reducing Home Heating Requirements - Weatherization

Since many households have converted to wood heating as a means to cut space heating costs, weatherization programs have been considered by some air pollution agencies as a means to reduce wood burning and thereby particulate emissions. If a household is weatherized to cut heating costs and that household as a result does not convert to wood heating then particulate emissions are indeed less than they otherwise would have been.

However, for the household which already is heating with wood, weatherization may not necessarily reduce emissions for two reasons, even though house heating requirements are reduced. First, the household may continue to burn as much wood as before weatherization and simply reduce reliance on conventional fuels such as oil, gas, or electricity. Secondly, an operator may begin to operate his wood stove at a reduced burn rate to avoid overheating his newly weatherized living space. This decreased burning rate results in a significant increase in particulate emission rates, which offsets the lower wood usage, resulting in no net decrease in emissions. However, emissions may be reduced by burning on fewer days. Because the weatherized house retains heat better, there may be no need for RWC on marginally cold or cool days. Emissions may also be reduced on burn days if the wood charge size is reduced.

In order to know for certain what happens to annual total emissions from an individual stove when a household is weatherized, ideally a set of experiments should be conducted as part of which stove operating time and conditions are monitored both before and after a dwelling's heating requirements have been significantly reduced. Unfortunately, no such experiments have been conducted to these authors' knowledge. In lieu of such information, two scenarios were chosen to give a range of possible emissions reductions from weatherization.

CASE #1

In the first scenario, it is assumed that annual wood burning will be reduced by about 33% for those households weatherizing (woodstove households only). This reduced wood use will occur by burning 15% fewer days[36] (on marginally cool days when space heating is no longer needed), and by burning 21% less wood per day on those days the stove is used. It is also assumed that most people (67%) will achieve the 21% less wood by further reducing the air supply to the stove and therefore reducing the burn rate, but will keep the wood charge size the same. For those households, the reduced wood burning rate (kg wood/hour) will result in a higher emission factor (g particulate/kg wood burned) according to Butcher's equation:

$$\text{emission factor}\ \left(\frac{\text{g particulate}}{\text{kg wood burned}}\right) = k\ \frac{m}{q}\ \frac{(\text{kg wood charged})}{(\text{kg wood hour})}$$

Since the total emissions equals the emission factor times the amount of wood burned, for these 67% of households the decreased amount of wood burned is offset by the increased emission factor resulting in the same total emissions on burn days as before weatherization (higher emission factor x less wood burned = same emissions).

It was further assumed that through an education program, the remaining 33% of the weatherized households could be persuaded to reduce the size of wood charge at the same time they reduce the burn rate, resulting in the same emission factor (g particulate/kg wood). The total emissions will therefore be reduced by the same percentage as the reduced wood burned (same emission factor x less wood burned = less emissions/burn day).

For those households using woodstoves and weatherizing, then, emissions will be reduced because of 15% fewer burn days and because some households (33%) will have reduced emissions on burn days. The emission reductions will be:

Fewer burn days: 15% days/yr X (100X emissions reduction/day) = 15% reduction of emissions/year

Lower emissions on burn days: 85% days/yr X 33% households X 21% emissions reduction/day = 5.9% reduction of emissions/yr

Total emissions reduction/year: 15% + 5.9% = 20.9%

It was also assumed that 60% of all households need weatherization, and 80% of those needing it will be weatherized, resulting in 48% of all households being weatherized (60% X 80% = 48%). If 70% of all woodburning households use wood stoves, then the total annual emissions reduction averaged over all woodburning households will be: 20.9% emissions reduction/year (weatherizated wood stove households) X 48% households weatherized X 70% wood stove households = 7.0% annual emission reduction for all RWC households.

CASE #2

For this scenario, some slightly different assumptions were used. As in Case #1, it was assumed that 48% of the households would be weatherized and that 70% of the RWC households have wood stoves. However, for this case it was assumed that wood use will be reduced 40% on burn days, and there will still be 15% of marginally cool days where no burning will occur. It was also assumed that all weatherized households will either burn on burn days in the same manner but fewer hours as before weatherization (same burn rate and charge size), or will reduce the wood charge size the same amount they reduce the burn rate (but burn the same number of hours as before weatherization). In either case, the emission factor (g particulate/kg wood) will remain the same after weatherization and the total emissions will drop the same amount as the drop in amount of wood burned (same emission factor X less wood burned = less emissions). The emission reductions from weatherized wood stove households would be:

Fewer burn days: 15% days/year X 100% emission reduction/day = 15% emission reduction/year

Lower emissions on burn days: 85% days/year X 40% emission reduction/day = 34% emission reduction/year

Total emissions reduction/year: 34% + 15% = 49%

Averaged among all RWC households (weatherized and unweatherized, fireplaces and stoves), the emission reduction will be

49% emission reduction/year X 48% of homes weatherized X 70% wood stove households = 16.5% emission reduction for all RWC households.

The assumptions used for these two cases are included in Table D9.

TABLE D9

Comparison of Assumptions and Resulting Emission Reductions for Two Scenarios Regarding the Effect of Weatherization

Common Assumptions For Both Cases:

- 50 million BTU/year heating required before weatherization:
  - 30 million BTU/year furnished from wood fuel
  - 20 million BTU/year furnished from conventional fuel
- 60% of all households need to be weatherized
- 80% of households needing it will be weatherized
- Households will heat on 15% fewer days after weatherization (no heat on marginally cool days).
- 70% of RWC households have woodstoves
- Weatherization will have a negligible effect on fireplace use since fireplaces have only a marginal heating function.

Case #1 Assumptions:

- Annual use of wood and conventional fuels will drop 10 million BTU's/year each (33% less wood, 50% less conventional fuel, 40% overall)
- 67% of households will reduce burn rate (kg wood/hour) but maintain the same wood charge size (kg/wood) after weatherization
- 33% will reduce burn rate and reduce wood charge size after weatherization
- Current oversized stoves will not be replaced by smaller stoves by the year 2000

Case #2 Assumptions:

- Daily sue of wood and conventional fuels will drop 40% after weatherization
- 100% will either reduce charge size and burn rate, or will maintain the same charge size and burn rate (but burn fewer hours) after weatherization
- Current oversized stoves will be replaced by smaller stoves during the normal replacement cycle

Annual Particulate Emission Reductions Averaged Over All RWC Households:

	Emission Reduction From No Burn Days	Emissions Reduction From Burn Days	Total Emission Reduction
Case #1	5.0%	2.0%	7.0%
Case #2	5.0%	11.4%	16.4%

. . . .

a. Weatherization of All Households

Thus the total potential emission reduction for airtight stoves which is estimated to result from weatherization (reduced emissions on burn days, reduced number of burn days) ranges from 10% to 23%. For an area where stoves contribute 70% of all wood burning emissions (e.g., fireplaces contribute 30%), total wood burning emissions would be reduced by 7% to 16% from such a program under these assumptions. Assuming that of the homes to be weatherized, 50% would be weatherized by 1990 and 100% by 1995, then the emission reduction benefits would be 3.5% to 8% by 1990 and 7% to 16% by 1995.

b. Weatherization of Only Households Installing New Stove/Furnace

If this strategy were to be modified so that weatherization would only be required of households installing a new stove, some greater circumvention likely would occur. If the circumvention level is arbitrarily assumed to be 30%, the 1995 and 2000 emission reduction benefits would be about 2.5% and 5%, respectively.

2. Improving Wood Fuel Quality

a. Selection of Wood Fuel with Higher Heating Value

Information is available on how energy content varies by wood species, but little is available on how emission rates vary by wood species. The energy or Btu content of different species of wood burned in the Pacific Northwest can vary by a factor of two. Douglas fir, the most commonly used wood type in the Pacific Northwest, contains 21 million Btu's per air dried cord (7673 But's per pound) while pine contains 16 million and oak contains 31 million Btu's per air-dried cord[38]. Values for 8 species are shown in Table D10.

Despite the fact that Douglas fir has 18% less Btu's per pound as Oak, there is no testing information on how particulate emission rates vary by wood species where the same stoves and conditions were used. Lacking information that emission rates are comparable per pound for different species, no emission credit can be claimed at this time from the use of wood with higher heat content.

Even if Oak wood did produce 18% less emissions per pound or kilogram as Douglas fir, supply constraints likely would limit the switching from Douglas fir to Oak to less than 10% of households currently burning Douglas fir which would yield a negligible emission reduction of less than 1.8% (18% x .10).

b. Moisture Content Control (Seasoning)

The traditional assumption is that burning dry wood can significantly reduce particulate emissions and creosote formation, presumably because lower moisture content wood requires less energy to vaporize moisture which should result in higher combustion zone temperatures, more complete combustion, and therefore, less emissions. The interrelationship between wood moisture content and particulate emissions is not understood completely, but some research has been conducted which provides insight. The research-

TABLE D10

Examples of Variation of Wood Fuel Heating Value With Wood Species

Species	Drying Time	Heating Value Million Btu per Air-Dried Cord
Cedar	6 - 8 MO.	20 medium-low
Douglas Fir	6 - 8 MO.	21 medium
Madrone	6 - 8 MO.	30 high
Oak	6 - 8 MO.	31 high
Pine	6 - 8 MO.	16 medium-low
White Fir	6-8 MO.	17 medium-low
Alder	18 - 24 MO.	21 medium
Maple	6-8 MO.	26 high-medium

Source: Oregon Wood Heat Handbook[38]

ers who have examined the relationship between wood moisture content and particulate emissions include Rudling and Ahling[11], Barnett[1i], Del Green Associates[20], Auburn University[39], and Shelton.[1k]

In the following discussion, fireplaces and stoves/furnaces are discussed separately with fireplaces discussed first.

1. Fireplaces - Moisture Content Effects

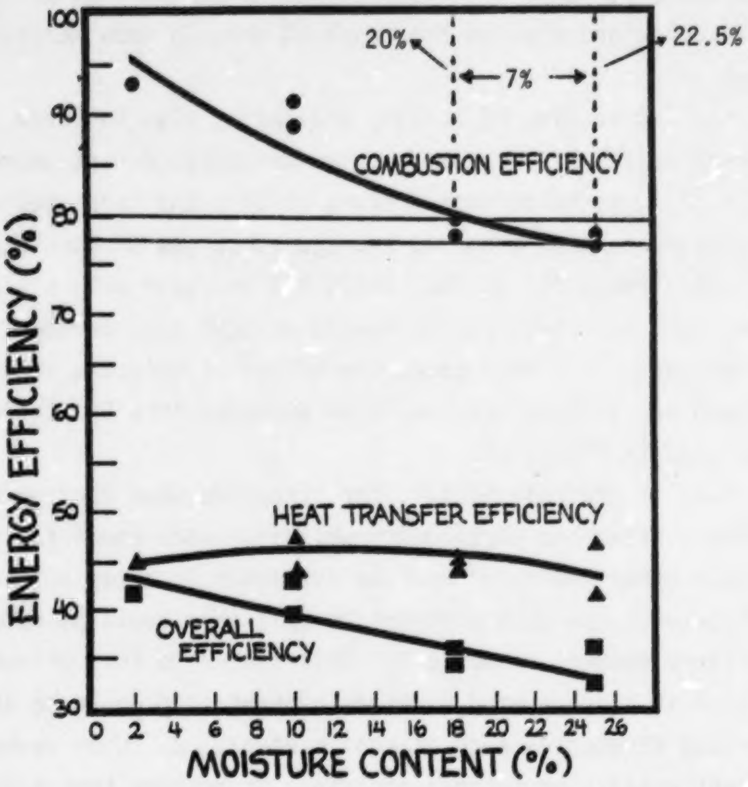
Shelton's emissions vs moisture content curve for burning wood in fireplaces is shown in Figure D6[1k]. Shelton did not directly measure emissions but did measure combustion efficiency. Since combustion efficiency is an indication of completeness of combustion, we have assumed for purposes of this analysis that the fraction [1 - Combustion efficiency] is a relative indicator of particulate emissions.

According to Figure D6, combustion efficiency decreases fairly steadily (i.e., emission's increase) as moisture content increases. For example, in this one set of tests, unburned combustion products constitute 22.5% (1-.775) of the total chemical energy in the unburned wood at 25% moisture content but only about 20% of 18% wood moisture content. This implies that emissions might be reduced by about 11% for fireplaces for a wood moisture content shift from 25 to 18% moisture content, which is equivalent to a 1.6% drop in emissions for each 1% drop in wood moisture content. However, while this relationship is the best available information, its applicability at wood moisture contents above 25% can be assumed but is not proven yet.

Noteworthy is the "flattening out" of Shelton's curve between 18 and 25% moisture content, which suggests fireplace emission rates may be less sensitive to wood moisture content changes at

FIGURE D6

Effect of Wood Moisture Content
on
Fireplace Combustion Efficiency



The dependence of efficiencies on moisture content in an open fireplace stove. Here power output could not be held constant but increased with decreasing moisture content. Fuel loads were of uniform size and were added when the previous load had been reduced to charcoal.

Source: Shelton[1k]

levels above 25%. Twenty-five percent is a moisture content level typically exceeded by wood burned in the Pacific Northwest.[19] Given this finding, we estimate that for wood between 25 and 35% moisture content, and burned in fireplaces, each 1% reduction in wood moisture content is associated with a 0 to 1.6% reduction in emission rates. Given the "curve flattening" between 20 and 25% moisture content, a reasonable assumption is that an .8% reduction in emissions results from each 1% drop in wood moisture content.

Limited testing by Rudling and Ahling also indicate that fireplace emissions decrease as wood moisture content decreases.[11] For fireplace tests conducted (Runs 11-14), the three tests with 19% moisture content wood had average stack gas CO concentrations of 310 ppm (range 110 to 560) while the one test with 41% moisture content wood had stack gas CO levels of 3200 ppm, or about a 10-fold increase. For this case, the effect of moisture content on emissions was greater than would be surmised from Shelton's curve as depicted in Figure D6.

Even if the relationship for fireplace wood burning between moisture content and particulate emissions were known for certain, one major other "unknown" must be estimated in order to derive an estimate of how much particulate emissions could be reduced by moisture content reductions. This factor is the percentage reduction in average wood moisture content that could be achieved by various strategies such as public education. When several different estimation methods are used, it appears that a 2% reduction in average wood moisture content is a reasonable estimate of what could be achieved by public education programs. These different estimation methods are discussed below.

Estimate Based on Hypothetical Distribution by Moisture Content

For the hypothetical analysis below, we assume that the distribution of wood by moisture content (m.c.) roughly can be approximated by assuming that 33% of the wood burned was 25% m.c., 33% has 30% m.c., and 33% has **35%** m.c.. Griswold[19] of Anchor Tools and Wood stoves (Portland, Oregon) has claimed that it is uncommon for wood stored in the Pacific Northwest to have a moisture content below 25%. If somehow all wood burned were to be dried longer **and protected more efficiently, such that all wood was to have a** 25% m.c., then a 5% reduction in average wood moisture content would result [(.33 X (35-25) + (.33 X (30-25)] + (.33 X (25-25)] = 5%. This appears to be a good upper level estimate.

However, no program is 100% effective in changing behavior, espcially when the change involves greater inconvenience (i.e., longer storage time). In the table below, hypothetical estimates are made of how much wood moisture **content would be reduced for** the three m.c. categories of 25%, 30%, and 35%.

Starting Wood Moisture Content	35%	30%	25%
Moisture content reduction within category assumed	20% reduce 10% = 2%	40% reduce 5% = 2%*	No reduction assumed achievable.
	20% reduce 6% = 1.2%	20% reduce 2% = .4%	
	20% reduce 2% = .4%	40% reduce 0% = 0%	
	40% reduce 0% = 0%		
	3.6%	2.4%	

* The 10% and 6% reductions assumed for 35% m.c. wood are constrained to 5% for 30% m.c. wood since it is assumed reductions below 25% are unlikely.

Based on the above table, if one-third of the wood is in each of the three m.c. categories, then for all wood these changes equate to a 2% reduction in average wood moisture content (.33 X 3.6%) + (.33 X 2.4%) + (.33 X 0%) = 2.0%. This value is 40% of the maximum potential reduction identified, which appears reasonable.

Survey Based Estimate

Data is not available on typical wood storage practices for the Pacific Northwest as a whole, but was collected for Portland, Seattle, and Spokane in Task 2B (Surveys)[40] in this study and for

Medford, Oregon in a 1981 O.D.E.Q. survey.[41] The DEQ survey found that households stored their wood as shown in Table D11 below. This distribution is considered to be more representative of the Pacific Northwest, because it is a true areawide survey, whereas the Task 28 survey was done in a single residential neighborhood. The results of both surveys are fairly similar.

TABLE D 11

Wood Storage Practices in Medford, Oregon
1981 State Survey Findings

Manner of Wood Storage	% of Households
Inside homes	0.5%
Garage or Shed	17.2%
Covered Outside	51.5%
Uncovered Outside	29.0%
Combination	1.8%

The storage category for which the greatest moisture content reductions could probably be achieved is wood which is stored uncovered outside. We assumed that 50% of this 29% of households could be "educated" to alter their wood storage practices (i.e., to outdoor covered storage) and that this would reduce wood moisture content from a 35% average to a 28% average (somewhat more than the 25% m.c. assumed to be best attainable in the Pacific Northwest climate). This would result in reducing average wood moisture content among all fireplace users by about 1.0% [(35-29) X .5 X .29] and emissions by .8% (.8% emissions drop per 1% m.c. change x 1.0% change).

Some moisture content reductions also could be achieved by the 51.5% who store their wood "covered outside". Of the households which reported they store their wood "covered outside", the plastic or tarp partial covering method used by many also could probably be improved. For purposes of this analysis, we assumed that about 33% of these households could make their coverings more protective and reduce average moisture by about 3%. This would result in reducing average wood moisture content among all fireplace users by about .5% (3% x .33 x .515) and reduce emissions by .4% (.8% emissions drop per 1% m.c. change x .5% change).

If people could be convinced to season their wood for longer periods, some additional reduction in average wood moisture content could be achieved. The O.D.E.Q. Medford survey found that 34.4% of households obtain their wood in September and October. The survey also reported that about half of households cut their wood over 12 months prior to the survey and about half cut their wood less than 12 months prior to the survey. For purposes of this analysis, we assume that about 17% of households burn their wood within 4 months or less of cutting. If wood cutting policies were altered by forest management agencies such as the USFS, BLM, and state forestry departments to allow wood cutting only from March through July, we estimate that the extra seasoning time could reduce the moisture content of wood from government lands by 5% or less. If 80% of wood supplies are derived from government land, these assumptions yield a reduction in wood moisture content for all wood of 0.7% (5% x .17 x .8 = .68) from the practice of restricting fall wood cutting on government lands, or an emission reduction of 0.6% (0.7% m.c. change X .8% emission rate reduction per 1% m.c. decrease = 0.56%).

However, given this relatively small achievable reduction for this strategy, it appears unlikely that these benefits are large enough to persuade the forest management agencies to change their practices. Forest management agencies prefer to have removeable wood residues removed as quickly as possible to allow faster replanting. Some of these agencies perceive this policy change would delay returning forest lands to a reforestable state.

The average moisture content reduction which is estimated to be achievable for strategies of adding covering or improving covering for wood stored outside is 2.1% (1.4 + .7 = 2.1). If fall cutting on government lands were politically feasible to restrict; and if such a program were implemented then average wood moisture content could be reduced by an additional 0.6%, but this strategy appears unlikely to be ever implemented because of its implications for forest management. A 2.1% moisture content from the first 2 strategies would yield a 1.7% emission reduction for wood burned in fireplaces (2.1% X .8% emission rate decreases per 1% m.c. decrease).

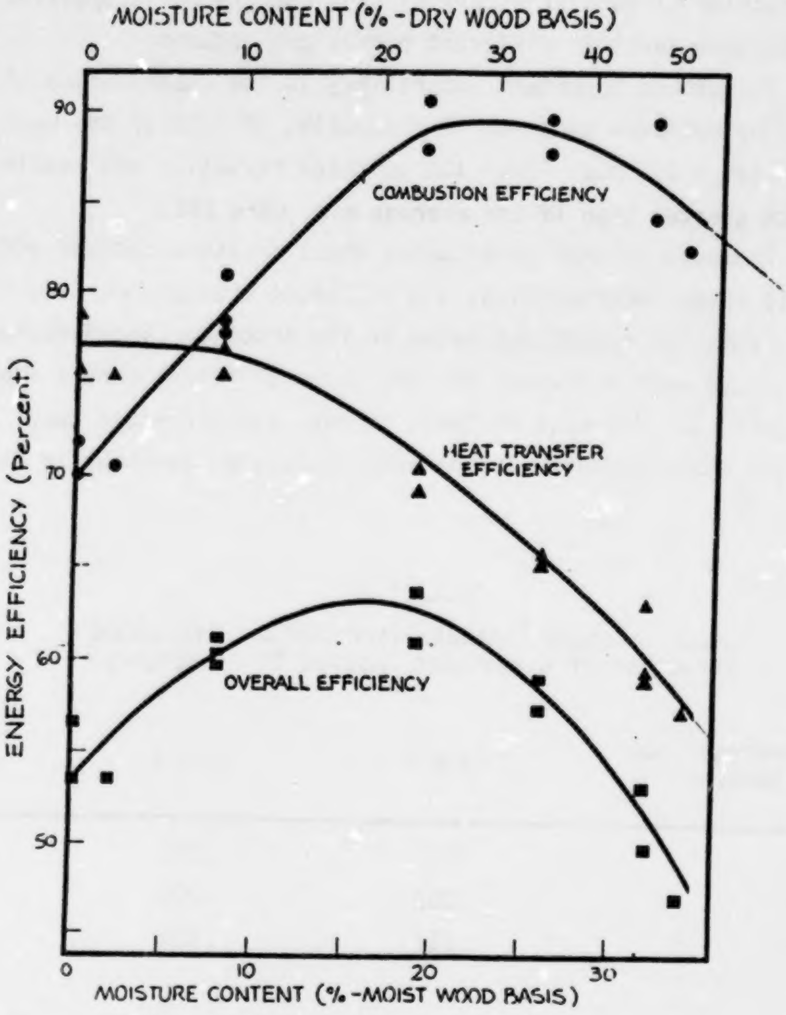
2. Stoves/Furnaces - Moisture Content Effects

The most complete set of data on how emissions from stoves/ furnaces can be expected to vary with moisture content is again available from work by Shelton.[1k] Shelton's findings for one air-tight stove are shown in Figure D7 below. Only combustion efficiency was measured and not particulate emissions. However, lacking better data, for purposes of this analysis we assume that particulate emissions are proportional to the fraction [1-combustion efficiency]. In this one set of tests, optimum moisture content was found to be between about 20 and 30% (wet basis).

Because the combustion efficiency curve is non-linear, significant uncertainties emerge when trying to draw conclusions about how much emissions could be reduced by changing wood moisture content. For example, in discussions with Shelton, although the shape of the combustion efficiency vs moisture content curve is thought to be similar for different stoves, the band of optimum moisture content range may be different for different stoves. This is significant because, if the curve were shifted about 5 percentage points to the right, a much lesser improvement in combustion efficiency would result from changing from 30% moisture content wood to 25% moisture content wood. This is illustrated in Figure D8

FIGURE D7

Effect of Wood Moisture Content on Stove/Furnace Combustion Efficiency



The dependence of efficiencies on fuel moisture content in an airtight stove. The air inlet setting was varied to maintain an average power output of about 17,000 Btu per hour for all moisture contents. The fuel load volume was approximately constant.

Source: Shelton[1k]

below. Two curves have been added to Shelton's combustion efficiency curve shown in Figure D7 as dashed-line curves. These two curves are assumed to have the same shape but are shifted 5 percentage points to the right and left. The reader can note how the fraction [1-combustion efficiency] changes for a specific moisture content level if different curves are assumed.

The second important uncertainty is the distribution of wood burned by moisture content. For example, if 100% of the wood burned had a 35% m.c. level the emission reduction achievable would **be much greater than if the average m.c. were 25%.**

In order to draw conclusions about moisture content effects despite these uncertainties, six different assumptions were evaluated. Emission reductions based on the fraction [1-combustion efficiency] were evaluated for the three different curves shown in Figure D8. For each of these curves, two different wood moisture content distributions were evaluated, as shown in Table D 12.

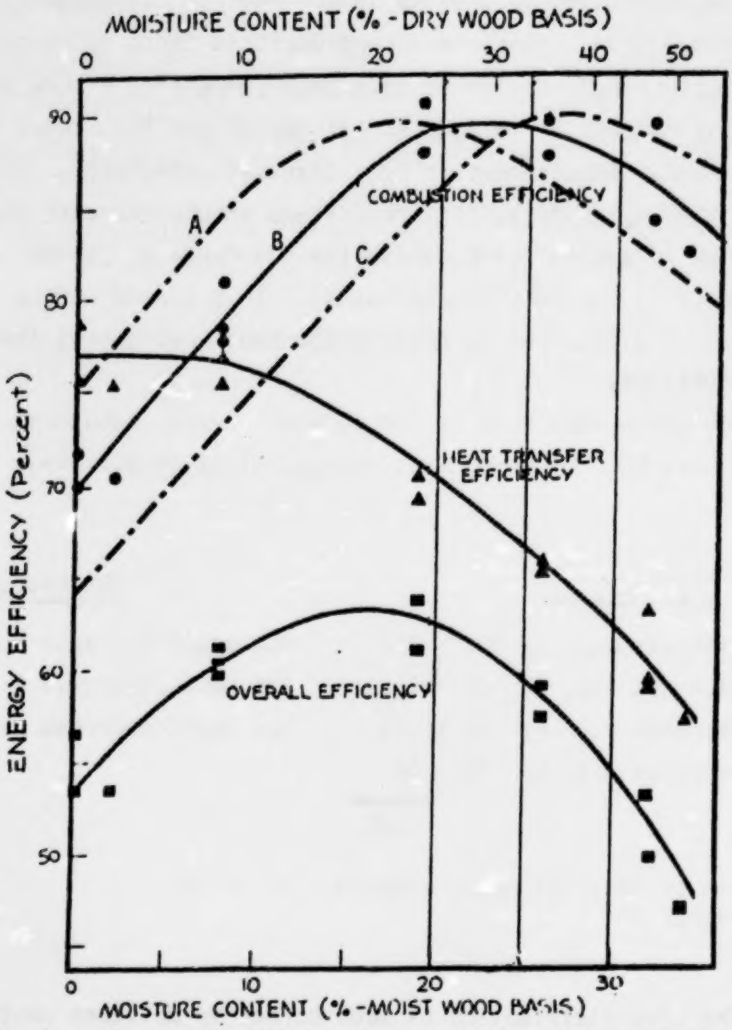
TABLE D 12

Wood Moisture Content Distributions Evaluated
(Fraction of Households Assumed In A Category)

Assumed Average Wood Moisture Content	Case 1	Case 2
25%	.333	.375
30%	.333	.500
35%	.333	.125

FIGURE D8

Three Assumed Moisture Content vs Combustion Efficiency Curves for Stoves/Furnaces



The dependence of efficiencies on fuel moisture content in an airtight stove. The air inlet setting was varied to maintain an average power output of about 17,000 Btu per hour for all moisture contents. The fuel load volume was approximately constant.

Source: Adapted from Shelton[1k]

For each of the above six scenarios, the achievable emissions reduction which would result from a 1% m.c. drop was estimated. Effects of reducing m.c. below 25% were neglected since this is considered difficult to achieve in the Pacific Northwest.

An additional factor was considered in these emission reduction calculations. As can be seen from inspecting Figure D7, as wood moisture content is reduced between 35 and 15%, there is a roughly linear improvement in heat transfer efficiency. This implies that moisture content reductions should increase overall efficiency in a consistent manner (in the range of 20-35% m.c. of interest in the Pacific Northwest). This should reduce the amount of wood required to achieve the same heat output and thereby reduce emissions.

For users with wood in the 30 and 35% m.c. category, it was assumed that the following m.c. changes might be achieved:

35% Category	30% Category
20% would decrease m.c. by 10% = 2%	40% would decrease m.c. by 5%* = 2.0%
20% would decrease m.c. by 6% = 1.2%	20% would decrease m.c. by 2% = 0.4%
20% would decrease m.c. by 2% = .4%	40% would decrease m.c. by 0% = 0.0%
40% would decrease m.c. by 0% = 0%	
3.6%	2.4%

* Constrained to 5% since m.c. reductions below 25% are considered unlikely.

The true distribution of wood burned by moisture content level is not known. If this distribution is 1/3 at 25% moisture, 1/3 at 30% moisture, and 1/3 at 35% moisture content, then average wood moisture content would be reduced by about 2.0% (.33 x (3.6% + 2.4%) = 2.0%). This is consistent with the

2.1% moisture content reduction assumed in the fireplace discussion above. If the distribution is better approximated by a 37.5%/50%/12.5% split for wood in the 25%/30%/35% moisture content level then average wood moisture content would be reduced by 1.65% [(.125 x 3.6) + (.5 x 2.4) = 1.65%] by the above assumptions.

The table below shows the estimated emissions reductions which are calculated for these six different scenarios, using the two moisture content reductions just described (2.0% and 1.65%).

Procedure Used to Estimate Stove Emission Reduction Potential from Reducing Wood Moisture Content

The fraction [1-combustion efficiency] was assumed to be proportional to RWC particulate emissions.

Calculations were made for six different cases:

Three different curves were assumed for moisture content vs combustion efficiency, as shown in Figure D8. One was the same as the combustion efficiency curve in Figure D7. The other two were assumed to be either 5% points to the right or left of the combustion efficiency curve in Figure D7.

Wood moisture content distribution was assumed to be represented by 1 of the 2 cases below:

33% of wood is in each of the three m.c. categories 25%/30%/35%.

12.5% assumed in 35% m.c. class

50% assumed in 30% m.c. class

37.5% assumed in 25% m.c. class

For wood in the 35% m.c. category it was assumed:

20% will drop to 25% m.c.

20% will drop to 29% m.c.

20% will drop to 33% m.c.

40% will remain at 35% m.c.

For wood in the 30% m.c. category it was assumed:

20% will drop to 25% (not 20% because PNW wood generally stays above 25% m.c.)

20% will drop to 25% (not 24% because PNW wood generally stays above 25% m.c.)

20% will drop to 28%

40% will remain at 30%

TABLE D13

Three Assumed Moisture Content
vs
Combustion Efficiency Curves for Stoves/Furnaces

Scenario	Curve Used	Moisture Distr. 25%/30%/35%	Emission Reduction Resulting
1	C	.333/.333/.333	5.5%
2	C	.375/.500/.125	3.5%
3	B	.333/.333/.333	10.5%
4	B	.375/.500/.125	8.1%
5	A	.333/.333/.333	11.7%
6	A	.375/.500/.125	9.9%
		AVERAGE	8.2%

The average reduction in RWC particulate emissions from all six scenarios is 8.2%. This applies to stove/furnace emissions. In the previous section an average 1.7% reduction in RWC particulate emissions from fireplaces was estimated for a similar reduction in firewood moisture content. From Task 3, for an area like Portland, Oregon, 1983 RWC emissions were estimated to be about 70% attributable to stoves/furnaces and 30% attributable to fireplaces. Thus, the overall reduction in total RWC particulate emissions, attributable to the wood moisture content reductions assumed here is estimated to be 6.2% [.7(8.2%) + .3(1.7%)].

The following is an example calculation for Scenario 3 above. An example calculation is presented below for the case where firewood is equally distributed among the three moisture content categories of 25% m.c., 30% m.c., and 35% m.c. - i.e., Case 3 previously described in Table D 12 as 33%/33%/33%.

From Figure D8 the quantity [1-combustion efficiency] is determined for each of the three moisture contents (25%, 30%, 35%). The magnitude of these quantities have been assumed to be proportional to the RWC particulate emissions from burning wood with these moisture content values. The values obtained for the quantity [1-combustion efficiency] are shown in column two below.

Combustion Efficiency	Moisture Content	Percentage of RWC TSP Emissions
16.2%	35%	40.9%
12.6%	30%	31.8%
10.8%	25%	27.3%

The values in column two were used to calculate the relative amount of total RWC particulate emissions which are attributable to wood in each m.c. category. This is shown above in column three. For the wood in the 35% category,

For the 20% which drops to 25% m.c., [1-comb. efficiency] shifts from 16.2% to 10.8%

For the 20% which drops to 29% m.c., [1-comb. efficiency] shifts from 16.2% to 12.2%

For the 20% which drops to 33% m.c., [1-comb. efficiency] shifts from 16.2% to 14.8%

For the 40% which remains at 35% m.c., [1-comb. efficiency] remains at 16.2%

Weighting these, the quantity [1-combustion efficiency] decreases from 16.2% to 14.03% which equates to a 13.4% reduction. However, while the change in the combustion efficiency vs m.c. is not linear, heat transfer efficiency changes in a linear fashion. Each 1% m.c. decrease yields a 1.5% improvement in heat transfer efficiency (i.e., 80 to 81.2%). Thus for wood in the 35% m.c. class, the average decrease of 3.6% m.c. levels [.2(10%) + .2(6%) + .2(2%)] corresponds to a 4.8% heat transfer efficiency improvement (Figure D7).

Thus reducing wood with 35% **moisture** content by an average of 3.6% in moisture content reduces RWC emissions in two ways. First, the emissions will be 13.4% less because the fuel is dryer. Second, 4.8% less fuel will be needed to produce the same heat output, because heat transfer efficiency is improved by that amount with the dryer fuel. The result of these is a 17.6% overall reduction (.866 x .952 = .824) in RWC particulate emissions for that (33%) portion of the firewood supply which originally had a 35% average moisture content. Since this orginally accounted for 40.9% of total RWC emissions, this reduction in moisture content decreases total RWC emissions by 7.2%.

Likewise for wood in the 30% category,

> For the 40% which drops to 25% m.c., [1-comb. efficiency] shifts from 12.6% to 10.77%
>
> For the 20% which drops to 28% m.c., [1-comb. efficiency] shifts from 12.6% to 11.87%
>
> For the 40% which remains at 30% m.c., [1-comb. efficiency] remains at 12.6%

Weighting these, the quantity [1-combustion efficiency] decreases from 12.6% to 11.72%, or a 7% reduction. Reducing the 30% m.c. wood by an average of 2.4% [.4(5%) + .2(2%)] thus reduces RWC emissions by a) 7% because of dryer fuel, and; b) 3.6% because increased heat transfer efficiency reduces the amount of fuel needed by this much (from Figure D7). The result of these is a 10.3%

decrease in RWC emissions from 30% moisture content wood (.93 x .964 = .897). Since 30% m.c. wood originally accounted for 31.8% of total RWC particulate emissions, this reduction in its emissions represents a 3.3% decrease in total RWC particulate emissions. For wood in the 25% m.c. category,

> No change is assumed to occur since it is difficult to dry wood in the Pacific Northwest below this level.

The total emission reduction is the sum of the effects from wood starting out in the 35% and 30% m.c. categories and is equal to 10.5% (7.2% + 3.3%). This illustrates the estimation, for Scenario 3 above, of the reduction in total RWC particulate emissions. This is one of six scenarios representing two hypothetical distributions of wood moisture content and three hypothetical curves representing the relationship of wood moisture content and RWC emissions represented by the quantity [1-combustion efficiency].

The average emissions reduction for all six scenarios (8.2%) is offered as the best estimate of the effectiveness of a strategy designed to reduce wood moisture content in reducing RWC emissions from stoves/furnaces. It previously was estimated using a similar scenario that fireplace emissions would be reduced by 1.7% because of reduced fuel moisture content. Assuming 70% of total RWC emissions is attributable to stoves/furnaces (by 1983, Task 3 projection), and thus 30% is from fireplaces, the overall reduction in total RWC particulate emissions from moisture content control is estimated to be 6.2% [.7(8.2%) + .3(1.7%)].

Other Related Research Findings

A second set of data is available from work conducted by Lars Rudling and Bengt Ahling of the Swedish Water and Air Pollution Research Institute.[11] Although particulate testing was not conducted, carbon monoxide emission rates were measured which are an approximate indicator of the particulate emission rate. Of five tests conducted at comparable conditions on an airtight wood stove, the CO emission rate averaged 600 ppm (range 320 to 750 ppm) for four tests with wood at 16% moisture content. The CO emission rates was 1500 ppm for the other run at 41% moisture content, which suggests an emission factor increase of 150% comparing the burning of 16% vs 41% moisture content wood in an airtight stove.

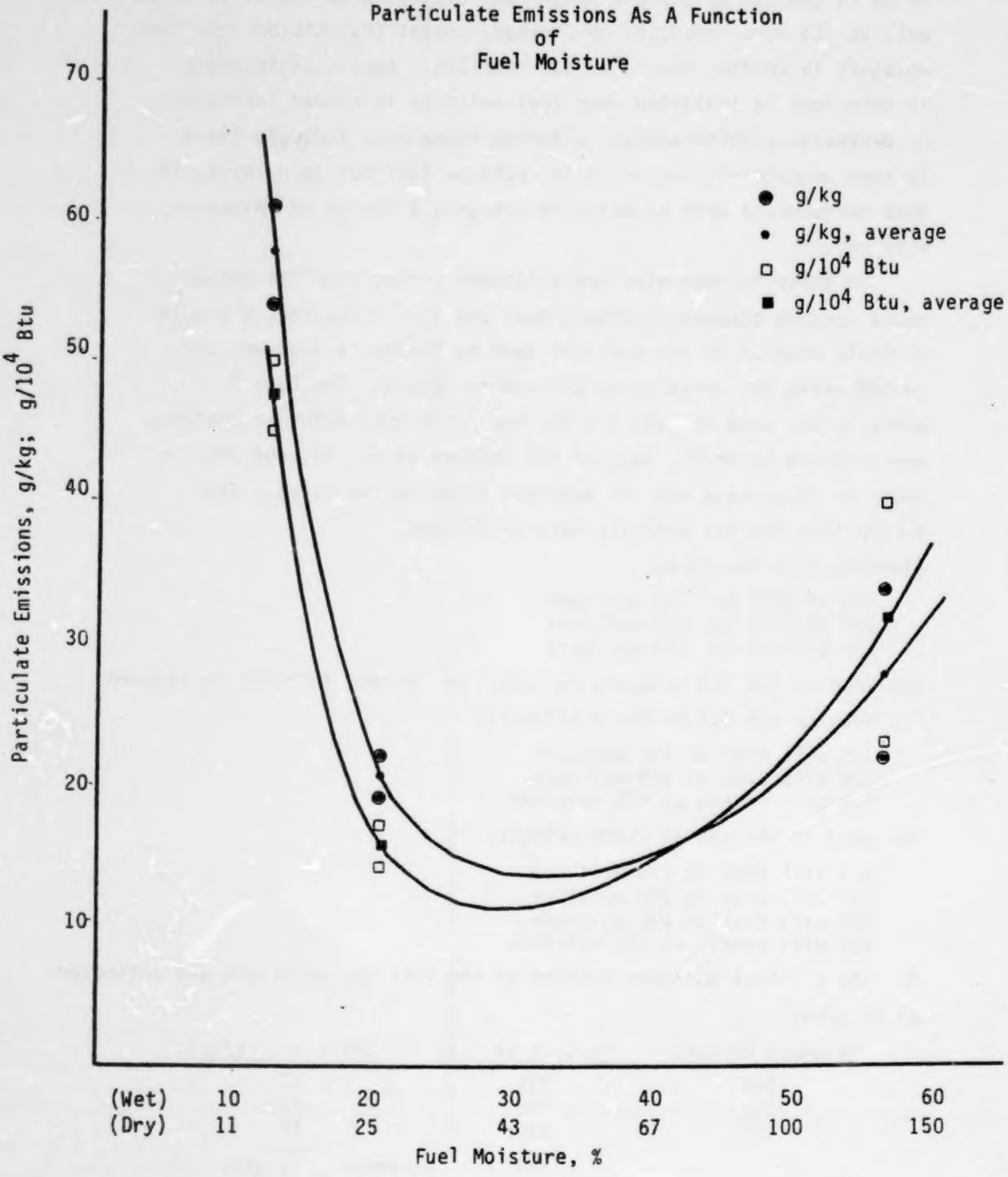
Shelton's finding for wood at 16% and 35% moisture content were compared to these results. If Shelton's curve (Figure D8) is extrapolated from 35% to 41%, the combustion efficiencies for 16% and 41% m.c. wood are 87% vs 78%, and the percentages of unburned combustion products are therefore 13% vs 22%. This would suggest emissions should be about 70% higher (22-13)/13 for the 41% m.c. wood compared to 16% m.c. wood. This is within a factor of two of the value (150%) derived directly from the Rudling/Ahling data for carbon monoxide emissions.

Barnett also has published limited stove test data which provide insight on the effect of moisture content on particulate emissions.[11] Of 51 tests conducted, the second and third highest emission factors were recorded for wood burning in airtight stoves with 3% and 24% moisture content wood as compared to the other 49 tests with wood in the 30 to 40% moisture content range. The findings that emissions were higher for 3% moisture content wood is consistent with Shelton's findings, but the observation of near maximum emission rates of 24% moisture content is not.

Lastly, moisture content research was conducted as part of Task 5[20] of this study. Nine different tests were conducted. A total of six test runs were conducted on an airtight stop stove for the specific purpose of determining the effect of fuel moisture content on emissions. Two tests were conduced at each of three different moisture levels -- "dry, medium, and high" moisture wood. Figure D9 presents the emission results from the six tests as a function of fuel moisture.

FIGURE D9

Particulate Emissions As A Function of Fuel Moisture



The results of these tests indicate the optimum fuel moisture to be in the 25 - 35 percent range (wet basis), which compares quite well to the work conducted by Shelton, except that the optimum fuel moisture is shifted upward to 30% from 25%. Again, an increase in emissions is indicated when fuel moisture is either increased or decreased significantly. Although these data indicate there is some uncertainty regarding the optimum fuel moisture level, it does corroborate that as moisture changes, a change in emissions will result.

In order to determine how emissions versus moisture content would compare between Shelton's test and Task 5 results, a single analysis similar to the analysis done on Shelton's data was conducted using the correlation derived in Task 5. The Case 3 scenario was used except that the beginning wood moisture contents were assumed to be 35, 40, and 45% instaed of 25, 30, and 35%, in order to compensate for the apparent shift in the curve. The assumptions for the analysis were as follows.

Starting Wood Moisture:

33% of fuel at 35% moisture
33% of fuel at 40% moisture
33% of fuel at 45% moisture

For wood in the 35% category no reduction in fuel moisture is assumed.

For wood in the 40% moisture category:

40% will drop to 35% moisture
20% will drop to 38% moisture
40% will remain at 40% moisture

For wood in the 45% moisture category:

20% will drop to 35% moisture
20% will drop to 39% moisture
20% will drop to 43% moisture
40% will remain at 45% moisture

For the original moisture content of the fuel the emissions are estimated at 15 g/kg.

Moisture Content	Percent of Fuel	Emissions (g/kg)
35%	33%	13
40%	33%	15
45%	33%	17
	99%	weighted average = 15 g/kg

The emissions from the fuel of reduced moisture content are:

Initial Moisture	New Moisture Content	Percent of Fuel	Emissions (g/kg)
35	35%	33% x 100%	13
40	35%	33% x 40%	13
	38%	33% x 20%	14
	40%	33% x 40%	15
45	35%	33% x 20%	13
	39%	33% x 20%	15
	43%	33% x 20%	16
	45%	33% x 40%	17
		weighted $\overline{x}$ =	14 g/kg

Therefore the percent reduction in emissions due to the change in moisture content would be 6.7% ((15-14)/15). This result compares reasonably well with the 10.5% emission reduction estimated using Shelton's relationship for combustion efficiency and indicates that the effect of fuel moisture content on emissions is significant. However, the data indicate that there is some uncertainty as to the actual value of the optimum fuel moisture content, although it is indicated to be near 30%, wet basis.

Perhaps one of the more significant conclusions which can be drawn from the data presented in Figure D9 is the decrease in emissions which can be expected to occur if wood is burned at the optimum fuel moisture content, as opposed to burning green, unseasoned wood (e.g., 55% moisture, wet basis). The data in Figure D9 indicate emissions could be reduced by 40% ((25-15)/15 g/kg) for a given fuel load. Assuming 15% of the current wood stove owners burn green wood and 75% of these could be educated to properly season the wood a reduction of 5% (.15 x .75 x .40) could be obtained for wood stove emissions and a reduction of 3.5% (.7 x .5) for total RWC emissions.

Auburn University Research[39]

Maxwell, Dyer, and Maples measured creosote deposition for different woods at different moisture contents. Although they concluded that higher moisture content wood produces less creosote several shortcomings in the test procedure make it impossible to generalize from this research to draw the conclusion that particulate emission rate always increases as wood moisture content decreases. First, although the test was designed to measure creosote rather than particulate emission rates, creosote deposition does not always correlate with particulate emission rates. Secondly, and most importantly, most of the test runs used wood with moisture contents well below the norm in most households. Nine of the 18 tests used wood with 0% m.c. and two of the 18 tests used wood with 8.3% m.c. Six of the 18 tests used wood with m.c. between 25 to 28% which is an insufficient differential upon which significant conclusions can be based. One test used 42% m.c. pine logs but none of the tests of wood with m.c. between 25 and 28% m.c. used pine logs. Thus the Auburn research cannot be used to draw any significant conclusions about how particulate emission rate varies with wood moisture content, at least within the moisture content range of primary interests, 25 to 35%.

3. Direct Restrictions on Wood Usage

The two strategy approaches evaluated in this category were a) episode controls, and; b) emissions density zoning. Assumptions and calculations for both are described below.

a. Episode Controls

If emissions from residential wood combustion can be reduced during peak pollution periods, then peak concentrations can be reduced. Several communities with air quality problems associated with wood burning, request residents to reduce or curtail wood burning during such episodes. The chief advantage of such a program is that it focuses on the time periods when emission reductions are needed the most. In the discussion below, several such programs are described and the potential benefits for the Pacific Northwest are calculated.

Albuquerque, New Mexico Program[21,42]

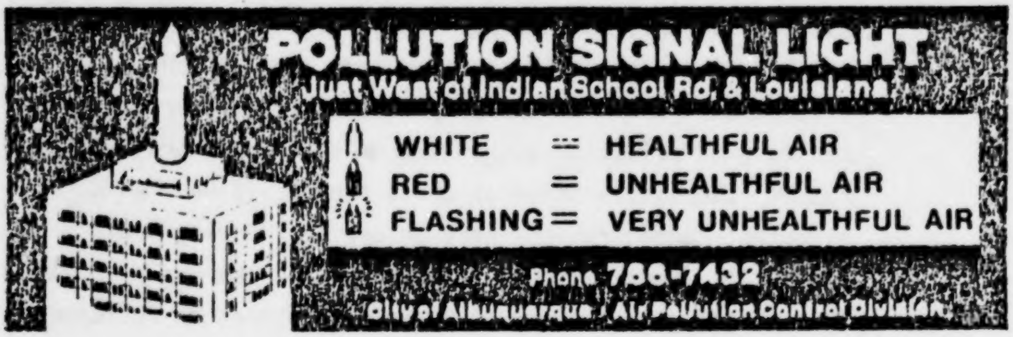
In 1981, the Air Pollution Control Division of the Albuquerque Environmental Services Department applied for and received a grant for $25,000 from the U.S. Environmental Protection Agency for the purpose of installing a telephone system and "pollution signal light" that would provide readily accessible information to the public on when high pollutant concentrations were occurring. During 1981 the "pollution signal light" was installed on the top of a 116 foot building in a commercial area surrounded by residences where high carbon monoxide concentrations had been recorded. The signal light has lights covering a 5 foot diameter tower 35 feet high, and the signal light is shaped in the form of a candle. The lights colors are changed depending on hourly CO concentrations. The light is operated so that it is white when hourly CO concentrations are below 13 ppm (Federal Standard = 9 ppm), red when hourly concentrations exceed 13 ppm, and blinking red when hourly concentrations exceed 26 ppm. At levels above 13 ppm, it is suggested that individuals reduce their usage of fireplaces and autos and at levels above 26 ppm a stronger request is made. Figure D10 on the following page shows a brochure which describes the pollution signal light system.

The system is operated between 5 p.m. and 11 p.m. during mid-November through mid-January, with one individual on duty adjusting the light based on hourly CO concentrations recorded remotely. Thus after set up costs, system operation requires about 42 manhours per week (6 hr per day x 7 days) or about 300 manhours per year (9 weeks x 42 hrs/week = 378), which at a loaded personnel cost of $20/hr would cost about $7600 per year.

Although the Agency perceives the signal light system to have beneficial effects in reducing wood usage during

FIGURE D10

Albuquerque Pollution Signal Light


POLLUTION SIGNAL LIGHT
Just West of Indian School Rd. & Louisiana
WHITE = HEALTHFUL AIR
RED = UNHEALTHFUL AIR
FLASHING = VERY UNHEALTHFUL AIR
Phone 766-7432
City of Albuquerque / Air Pollution Control Division

THE "CANDLE" – ALBUQUERQUE'S HOLIDAY AIR POLLUTION SIGNAL LIGHT

The holiday season is a time of reoccuring nighttime carbon monoxide problems The best way for you to be aware of air pollution conditions during this time is by checking the air pollution signal light the holiday CANDLE

WHAT TO LOOK FOR

A changing color CANDLE will be placed on top of a prominent building just south of Coronado Center to help you know when air pollution problems occur The color changes will indicate the conditions each night during the holidays We have unhealthful carbon monoxide conditions about half the nights in December The "CANDLE" may change several times during the night

HOW YOU CAN HELP

A WHITE CANDLE means that the air is "healthful" and it's OK to ENJOY YOUR FIREPLACE AND NORMAL DRIVING ACTIVITIES

A RED CANDLE means that the air is "unhealthful" and it is SUGGESTED THAT YOU NOT USE YOUR FIREPLACE OR DRIVE YOUR CAR IF AT ALL POSSIBLE

A RED CANDLE with a FLASHING FLAME means "very unhealthful" air This is a TIME TO NOT USE YOUR CAR OR FIREPLACE AND TO AVOID EXPOSURE TO THE OUTSIDE AIR

IF YOU CAN'T SEE THE CANDLE

A recorded telephone message will be available and updated each hour throughout the evening until midnight Just dial 766 S*M*O*G (7664)

THANK YOU FOR YOUR HELP

Thanks from your local Air Pollution Control office and the many citizens that are concerned about clean air

AIR POLLUTION CONTROL DIVISION
CITY OF ALBUQUERQUE
924 Park Ave SW
Phone 766 7432

This project is sponsored by the Albuquerque/Bernalillo County Air Quality Control Board, Robert Luna, Chairman "episode periods", the system only has been in operation for one winter season to date (winter 81-82). The peak days CO concentration was 27% lower during winter 81-82 than the previous year, but it is not currently possible to quantify how much of this differential is attributable to differences in weather, decreases in wood and auto usage because of the light system, or decreases in wood usage for other reasons.

Of the $25,000 grant, $9,000 was spent on the tower and lights, and $8,500 was spent to secure installation approval from the 116 foot high apartment building.

Missoula, Montana Program[22]

Since 1978 the Missoula County Air Pollution Agency has had an "episode control" program under which residents are requested not to burn wood (unless it is the sole source of heat) when pollutant concentrations are high. The program was modified in December 1981 such that curtailment of wood burning is a requirement for househlds at the second stage of "alert" severity, except for households which heat only with wood.

An automated particle monitor (APM), purchased in 1978 for $15,000, provides hourly average TSP levels. When particulate concentrations exceed 150 $\mu g/m^3$ and a meteorological analysis suggests that poor dispersion conditions will continue, the Agency, among other actions,

1. advises citizens via public media of the ALERT
2. requests citizens to discontinue use of residential solid fuel burners, and
3. requests citizens to limit automobile driving to necessary trips only.

When levels of 300 $\mu g/m^3$ occur and continued poor dispersion conditions are forecasted a "WARNING" is issued which results in the following Agency actions[43]:

1. citizens are advised of "WARNING" by public media
2. citizens are "strongly advised" to eliminate all non-essential driving, and
3. The discharge of visible emissions from residential solid fuel burners is prohibited, unless that equipment is the only heat source.

The third feature above is the regulation of greatest interest. The specific language is shown below:

> "No person shall cause, allow, or discharge visible emissions from any residential solid fuel burner unless such residential solid fuel burner is the sole source of heat. A person discharging visible emissions shall have the burden of affirmatively establishing that the residential solid fuel burner is the sole source of heat. For sources other than a residential solid fuel burner, no person shall cause, allow or discharge visible emissions from any source unless such source has a State or County air contamination permit."[43]

No "WARNINGS" (second-stage episode) were issued during winter 1981-82, but the Agency did assess public response to the requests for reduced wood burning during the "ALERTS" which occurred. Based on observations of whether visible smoke was being emitted from 194 wood-burning homes on six random afternoons per month, the Agency determined that requests for wood burning cutbacks resulted in 36% less households burning wood on a voluntary basis.[21]

In a survey conducted in Missoula in 1980[44], 59% of respondents said they would support a regulation banning wood heating on poor air quality days. Over 70% said they did cooperate with the voluntary ban during alerts. Thus although there is no experience yet with compliance on "WARNING" days (+300 $\mu g/m^3$ TSP) when visible emissions are prohibited from wood burning households, a 75% reduction in wood burning under these conditions is assumed for purposes of this analysis.

TSP levels from the APM are telemetered into a central computer system. The Agency which accesses the State Air

Quality Bureau computer, spent $13,000 for peripheral equipment which provided benefits beyond the episode control system (i.e., word processing capability, printing capability, modelling, etc.). The two telephones which provide air quality updates cost $280 initially. The annual cost for the two lines is about $750/year and the "hunting" line system (to switch calls between phones) costs $400/year. About 30% of one professional's time is required during the 5 month winter period to coordinate the system. For an assumed loaded salary cost of $30,000 per year, this equals about $3750 in annual labor costs ($30,000 X 5/12 X .3 = $3750).

Application In the Pacific Northwest

In Oregon, the Department of Environmental Quality is prohibited from regulating household space heating equipment.[12] However, the effect of requests to voluntarily curtail woodburning can be estimated based on experience in Missoula. If a widespread public education campaign were conducted as in Missoula, it is estimated for purposes of this analysis that a 33% reduction could occur in wood heating on "episode days", which would yield a 33% reduction in emissions on those days.

Based on a ratio of peak day concentration to average winter day concentrations of 2.5*, the reduction in average winter particulate concentrations can be calculated, depending on the number of episode days.

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* Larsen[23] first identified this relationship which resulted in setting 24-hour particulate standards at 2.5 times the level of annual particulate concentrations (150 vs 60 $\mu g/m^3$ TSP).

# Episode Days In A Geographical Area	Calculation Basis	Estimated Reduction In Ave. Winter TSP Concentrations
4	(33% Reduction) X 4 days/150 days X 2.5 average concentrations =	2.2%
9	(33% Reduction) X 9 days/150 days X 2.5 average concentrations =	5.0%
12	(33% Reduction) X 12 days/150 days X 2.5 average concentrations =	6.7%
15	(33% Reduction) X 15 days/150 days X 2.5 average concentrations =	8.3%
18	(33% Reduction) X 18 days/150 days X 2.5 average concentrations =	10.0%
20	(33% Reduction) X 20 days/150 days X 2.5 average concentrations =	11.1%
25	(33% Reduction) X 25 days/150 days X 2.5 average concentrations =	13.9%

Thus for an area with typically nine winter days with particulate concentrations exceeding 150 μg/m^3, a 33% reduction in wood burning (resulting from voluntary requests) should reduce the impacts from wood burning on those episode days by 33% and average winter wood burning impacts by 5%.

b. Emission Density Zoning Effect On Emissions

Emission density zoning is sometimes suggested as a means to limit emissions from pollution sources such that acceptable pollutant concentrations are not exceeded. Clearly this approach has greatest potential for large emission sources who must obtain a pollution discharge permit as a condition of operation - for small sources such as wood stoves, if limits were to be set which limited the number of stoves per square mile, there would obviously be compliance and enforcement problems. Oregon statutes which prohibit the State from regulating household space heating devices also would make this approach impossible at this time. Nevertheless, in the discussion below, estimates are made of how much future emissions would be reduced, if stove installations were to be limited to 1984-levels, assuming levels of compliance. The estimates are based on the projection of future wood usage from Task 3 for Portland, Seattle, and Spokane. Table D 12 below shows how much total wood burning emissions would be reduced by 1990 and 2000 if new stove installations were not permitted after 1984 if 50% compliance is assumed.

TABLE D 14

Reduction in Expected 1990 and 2000 RWC Emissions If New Stove Installations Were Not Allowed After 1984 and 50% Compliance Occurred*

City	Emission Reduction by 1990 Compared to Expected 1990 Levels	Emission Reduction by 2000 Compared to Expected 2000 Levels
Portland	3.2%	27.3%
Seattle	3.9%	3.9%
Spokane	3.7%	13.7%

Since the greatest growth in wood burning in stoves is projected for Portland, if that growth were somehow precluded then the greatest emission reduction would occur in Portland. However, due to compliance problems, legality problems, and general public **nonacceptance** of such constraints, no practical emission reduction benefit appears achievable by this strategy.

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* Based on projected growth in the wood usage by stoves/furnaces from Task 31.[31]

C. Improving Operating Practices

Operating procedures can have a significant influence on burning unit emission production. In the discussion below, assumptions and calculations are presented for the following potential strategies:

1. Initial selection of burning units - "Sizing"
2. Operating Technique Modifications
   a. Discouraging Airtight Stove Operation
   b. Charging Larger Pieces of Wood
3. Periodic Inspection of RWC Equipment

1. Initial Selection of Burning Units - "Sizing"

The proper sizing of a wood stove is sometimes advocated on the basis that a larger stove often produces so much heat for the room in which it is located that air supply must be severely restricted - resulting in poorer combustion efficiency and higher creosote deposition and air pollutant emissions. Conversely, a smaller stove is alleged to "burn hotter" with resulting higher combustion efficiency and less creosote and emissions. In the discussion below, the effects of stove size on emissions are analyzed based on a review of the available information on how operating factors influence emissions.

In summary, it appears that the chief benefit of smaller stove sizing derived from the result that smaller amounts of wood are generally charged when reloading due to the smaller firebox capacity and smaller loads result in a hotter fire with better combustion efficiency and lower emissions. Regarding the effect on "burn rate", assuming that a room's or household's heating requirements remain constant, when a smaller stove is utilized, it appears likely that operators will generally still seek the same heat output (in Btu's/hour) and thus the same volume of wood can be expected to be burned per hour (neglecting small changes in overall efficiency) which means burn rate does not change. Several issues are discussed below:

- Burn rate effects
- Size of fuel charge effects
- Inconvenience issues
- Possible efficiency changes

Burn Rate Effects

If the same room or house heating requirements exist, the same approximate number of Btu's/hour are required to maintain comfortable temperatures. Thus merely changing stove size does not alter burn rate (expressed in Kg wood/hour) and benefits cannot be attributed to burn rate changes when stove downsizing occurs, **unless the charge size is also reduced.**

Fuel Charge Effects

Research by Butcher indicates that the intensity of a fire is what most influences emissions. Intensity of a fire can be thought of as the heat release rate from ongoing combustion divided by the amount of wood charged. For the same wood charge, burning with a greater heat release rate results in a more intense fire and less emissions and for the same heat release rate, a smaller wood charge results in a more intense fire and less emissions. In both the above cases a more intense fire means there is more heat released per pound charged. This relationship was described in equation form by Butcher in 1979[10]:

$$y = 10.34\ m/q - 1.18$$

where

y = emission rate in g/kg
m = fuel charge in kg of wood
q = combustion rate in 10,000 Btu's output/hour

Battelle also found that emission rates increase with increasing charge size, when burn rates are held constant. Based on stove tests where carbon monoxide and total hydrocarbons were measured, Battelle[1m] noted that:

> "The amount of wood loaded into the stove will have a large influence on the amount of pyrolysis products leaving the stove. The emissions increase with the increase in wood inventory at the same burning rate due to the increased quantity of wood exposed to heat and thereby subject to preburning pyrolysis."
>
> "To demonstrate the effect of increased wood inventory in a stove, two tests were run. In one test, 12.9 lb of wood was burned and in another 41.9 lb. The wood was the same for both tests (oak 4x4's) and the stove was operated at the same air setting on the same day. The tests were run using the side draft mode of burning."
>
> "Table II compares the two tests, demonstrating that, as the wood inventory increases, the emissions increase. Although the burning rates for the two tests were essentially the same, the large charge resulted in approximately twice the emissions."
>
> "Stoves that keep the wood from pyrolyzing by isolating the wood inventory from the heat during combustion should reduce emissions. Since most existing stove designs do not isolate the wood inventory, the only course open to the operator to reduce emissions from this mechanism is to add small quantities of wood more frequently."

Size of Fuel Charge Effects

No change in burn rate or combustion rate can be attributed to a change in stove size, but a smaller stove will have a smaller firebox which will mean that generally smaller amounts of wood will be charged each time. This means "m" in the above equation is smaller. Thus if a stove with 25% smaller firebox capacity is installed, it can be assumed that average "charge size" ("m") will be reduced by 25% which reduces the emission rate by 25%.

Since emissions per day equal the emission factor times the wood burned per day, and wood burned/day does not change, the emissions per day can be evaluated to drop by 25%:

Emissions/Day = (Emission Factor) x (Wood Burned Per Day)
Grams TSP/Day = Grams TSP/kg wood x kg Wood/Day
Decrease 25%   Decrease 25%   Remains Constant

Thus the benefit from sizing appears to result from the resultant smaller typical charge size in a smaller stove.

Convenience Trade-offs

In the eyes of a stove operator, convenience issues strongly influence how a stove is burned. Many operators burn at slow burn rates because it is more convenient to reload the stove at longer intervals. Many stove operators like to damper the air supply at night so coals will remain in the morning and the fire will not have to be restarted. For households where all adults generally work, a slow burn rate throughout the day also is desirable.

When a smaller stove is utilized, since the firebox volume is smaller, lesser amounts of wood can be charged each time and for the same burn rate or heat output, reloading will be required on a more frequent basis. This issue is the factor which most encourages larger stove purchases by operators and forms the greatest barrier to changing behavior so that individuals purchase smaller stoves.

Two other factors work to encourage smaller stove sizing. A smaller stove contains less materials and thus generally costs less than a larger stove, assuming equal complexity of design. Also a smaller stove by virtue of its greater burning intensity will generally burn hotter and have less creosote deposition.

Stove manufacturer's representatives acknowledge many stove purchasers' desire for long burning capability in a stove. At the February 1982 Wood Heating Alliance Trade Show in Louisville, Kentucky, one manufacturer even boasted that his stove had sustained a burn for 48 hours. The issue of reloading inconvenience will limit the degree to which stove operators will be willing to "down size", unless continuous feeding systems such as chip burners have significant market pentration.

Efficiency Issues

Overall efficiency is the product of combustion efficiency and heat transfer efficiency. A "hotter" or more intense burn will generally have a higher combustion efficiency. However, to assess how overall efficiency changes, changes in heat transfer efficiency must be factored in. Although research on how heat transfer efficiency varies with burning intensity is limited, under some conditions a hotter or more intense burn will lead to hotter stack gas temperatures and a lesser heat transfer of the additional Btu's in the hotter stack gas. This means that a hotter burn will not necessarily result in higher overall efficiency since the combustion efficiency increase may be offset by a decrease in heat transfer efficiency.

Barnett has claimed that overall efficiency generally plateaus between a 2 and 4 pound/hour burn rate. This is approximately the burn rate range which is believed to represent typical practice in Western Oregon and Washington. Also, efficiency testing results for both a catalyst stove (Webster Oak) and a secondary combustion stove (Jotul 201) show that these units have higher overall efficiency at lower burn rates than higher. Although these stoves may represent a different category of stove behavior because of the secondary combustion which they achieve, based on these results, no change in overall efficiency can be attributed to the downsizing of stoves.

Discussion with stove technology experts[24] suggest that average firebox volume will decline over the next 20 years. Day believes a 40% reduction in average stove firebox volume will occur by 1990. The degree of downsizing that will occur cannot be known for certain, but these authors estimate that additional "downsizing" of 10% by 1990 and 15% by 2000 could occur as a result of a strong public education program which would yield an additional emission reduction of 10% by 1990 and a reduce beyond that of 5 percent by 2000. Since wood stoves/furnaces are assumed, for purposes of this analysis to account for about 70% of all RWC emissions by the mid-1980's, the sizing strategy approach could reduce overall RWC emissions by about 7% by 1990 (10% x .7), and about 10.5% by the year 2000.

2. Operating Technique Modifications

a. Discouraging Airtight Operating Of Stoves

Operators often restrict air supply on airtight stoves, either as a means to limit a stove's heat output so that comfortable room temperatures are not exceeded or for convenience to extend the length of time between refuelings. Restricting air supply slows down the burn rate since the amount of oxygen available in the combustion zone limits the rate of combustion of the wood. The effect of burn rate on total emissions is discussed as a Key Topic early in this Appendix.

Regarding airtight operation, it appears that discouraging airtight operation, or increasing burn rates only reduces total emissions if the operator burns for fewer hours per day when he shifts to a faster burn rate. Unless an operator reduces the number of hours per day that the stove is in operation, the benefits of a lower emission factor from a higher burn rate is counterbalanced by the increased amount of wood burned per day when more pounds wood per hour are burned. This relationship is shown below.

The best equation to describe burn rate effects is Butcher's:

$$\underset{(\text{g/kg})}{\text{Emission Rate}} = \underset{(\text{constant})}{K} \quad \times \quad \underset{\dfrac{(\text{wood charge in kg})}{(\text{Btu output in 10,000 Btu/hr})}}{m/q}$$

If burn rate is doubled from 1 to 2 kg/hour then the emission factor is halved since the "q" term which is in the denominator of the equation is doubled. However, whereas a 10 kg charge will last 10 hours at a 1 kg/hour burn rate, it will last only 5 hours at a 2 kg/hour burn rate. If the operator will modify operation so that he is willing to burn 5 hours at twice the rate and then not operate the stove for 5 hours, the emissions in that 10 hour period will be halved. This, however, seems unlikely to occur unless a heat storage mechanism is employed since the house would then have no heat source for a 5 hour period.

Comfort factors also make it unlikely that operators will be willing to shift to a burning hotter/not burning alternating pattern.

If burn rate is doubled, the stove will putout twice as much heat to the room where the stove is located which is likely to make the room uncomfortably hot. Quite simply, operators restrict air flow in order to control room or household temperature, and it appears unreasonable to expect that many will shift to a burning hotter/not burning alternating pattern, because that will result in large swings in the temperature of living areas. Since such a behavior change appears unlikely to occur, these authors assign no emission reduction benefit to this strategy.

b. Charging Larger Pieces of Wood

Both Barnett and Battelle have noted that smaller sized logs burn with higher emission rates than larger logs when burn rates are held constant. Battelle's results are based on CO and total hydrocarbon emissions. Battelle explains the phenomenon as follows:

> "The size of wood has a large effect on the rate of pyrolysis. The smaller pieces of wood result in: a shorter distance for the pyrolysis products to diffuse, a larger surface area to mass ratio, and a reduction in the time required to heat the entire piece of wood."[1m]

Barnett hypothesizes similarly that the "surface area to wood volume" is the key parameter:

> "... results indicate that log diameter has a large effect on emissions. Undoubtedly, the surface area to wood volume relationship is a key factor. Thin logs have a large surface area volume ratio. Therefore, these logs heat up relatively fast and then release their volatiles at a fast rate. This process is further aided by the large surface area of the logs through which volatiles are released."[1i]

Barnett developed a best fit equation for a thin-walled convective heater operated with a stove surface temperature of 300°F:

$$y = 11.3 - 9.9\ [\log\ (\text{log size})]$$ [1i]

where

y = TSP emission rate in grams per pound

log size = log diameter in inches

On a grams per kilogram emission rate basis the equation can be converted to:

$$y = 24.9 - 21.8\ [\log\ (\text{log size})]$$

Table D 15 below shows the different emission rates for logs with diameters ranging from 1/2 to 10 inches in Column 2. Column 4 shows the % emission reduction which results from increasing the baseline log size by 2". As can be seen, increasing log size by 2" is predicted to decrease emission rates by about 33% within the range of common log sizes which can be used.

TABLE D15

Effect of Log Size on Particulate Emission Rates

Log Size (Inches)	Predicted **Emission Factor** (g/kg)	Assumed Log Size Change From	**Resultant %** Emission Rate Decrease
.5	31.5		
1	24.9		
2	18.3	2" to 4"	36%
3	14.5	3" to 5"	33%
4	11.7	4" to 6"	32%
5	9.7		
6	7.9		

Asking stove operators to increase the average piece size used requires little sacrifice on their part - in fact less splitting requires less work. Since such a behavior change does not result in any additional inconvenience to the operator, the chances of increasing the average piece size via educational programs appear promising. These authors estimate that 50% of homeowners could be convinced to do less splitting such that their average piece size was increased by 2 inches. On this basis, a 13% emission reduction from the stove population could be achieved with little operator sacrifice (33% x .50 = 16.5%) Assuming 70% of total RWC emissions **are attributable to stoves/** furnaces, this affords an 11.5% overall reduction in RWC emissions.

3. Periodic Inspection of RWC Equipment

The strategy is based on the concept that combustion equipment can deteriorate in performance over time, that inspections can identify such deterioration and that maintenance can restore the equipment to the original level of performance. In Germany and Switzerland, large combustion equipment is subject to annual or more frequent inspection requirements with follow-up maintenance to correct deficiencies required.

For small residential stoves and fireplaces several means can be identified by which an inspection program could yield emission reductions. These are discussed below.

First, if catalyst stoves ever constitute a significant share of the stoves in use, an inspection program could speed identification and replacement of non-working catalytic combustors. For example, Corning Glass Works, a major manufacturer of stove catalysts, estimates their catalyst has a 6000 hour lifetime.[26] For a stove operated 20 hours/day and 5 months per year, this equates to about a 2 year lifetime. It is reasonable to expect that many operators will be slow to replace a catalyst after deterioration, because of "inertia", lack of perception of catalyst non-performance, and because of the $75 to $100 replacement cost.

Second, as stove designs become more sensitively optimized, increased stove maintenance may become necessary to maintain the original high level of performance. This appears to be a more likely requirement for stoves with 95% combustion efficiency with intricate air introduction arrangements than for simple stoves with 80% combustion efficiency. An inspection program might be able to identify and correct such deteriorations in performance.

Thirdly, if an inspection program were to focus on counselling the operators whose chimney stacks emit especially dense plumes, they could advise those operators on how they might change operating practices to reduce creosote deposition and stack emissions. Focusing on "worst offenders" could yield the greatest benefits for the time spent - the 10% of stoves which produce greatest emissions per day probably account for more than 20% of total stove emissions.

Despite the above potential benefits from inspection programs, several factors make inspection programs unlikely to be implemented as a government-imposed strategy in most communities. First, some states such as Oregon prohibit environmental agency regulation of home space heating devices.[12] Secondly, there would be significant public **opposition to a program under which** inspectors had authority to enter households and require equipment modifications. These factors lead us to conclude that **an inspection program is not a feasible regulatory strategy for most** communities for reducing emissions and thus no emission reduction credit is assigned to this strategy.

One factor will work to promote safety inspection - the increased fire hazards associated with solid fuel heating equipment. In Oregon 33% of the fires in single family dwellings are associated with solid fuel burning equipment (i.e., wood or coal).[25] In France, households with solid fuel heating equipment are assessed significantly higher fire insurance charges unless they submit proof of passing a safety inspection on an annual basis. If a safety inspection program were ever implemented, there would be increased chances for an emissions inspection program to be "piggy-backed" on the safety inspection program.

APPENDIX E

Keppner-Tregoe Evaluation of Final Fifteen RWC Control Strategies

This appendix describes the application of the full (three-step) Keppner-Tregoe process to rank the final fifteen RWC Control Strategies described in Section VI and summarized in Table E1. Section III of this report describes the Keppner-Tregoe evaluation process.

I. MUST CRITERIA

All fifteen strategies were judged to satisfy all five MUST criteria described in Section III (Table 1), with the following caveat. Implementation of some strategies or strategy elements would require enacting or adopting specific legal authority (e.g., mandating weatherization of homes) or establishing financing programs (e.g., weatherization loans). Such authority or financing would have to be "in-place" before a strategy could be approved by EPA as part of a State's Clean Air Act Implementation Plan (SIP), thereby "meeting all legal requirements established by the Clean Air Act" (MUST criteria #2). The final fifteen strategies have some precedents for all or most of their major control elements. Accordingly, these strategies are considered capable of meeting MUST criteria #5.

II. WANT CRITERIA SCORING

The general process of assigning WANT criteria scores was described in Section III D. The twelve WANT criteria to be used were described in Section III (Table 2) and their weighting factors in Appendix A. An example of a decision framework for assigning scores to strategies for a particular WANT criteria was described in Section IV B.

TABLE E1

Final Fifteen RWC Control Strategies Evaluated

Strategy #1	Testing/Certification as Prerequisite to Sales or Installation of New Stoves/Furnaces
Strategy #2	Strategy #1, with 33% Tax Credit ($400.00)
Strategy #3	Testing as Basis for Mandatory Labeling of New Stoves/Furnaces Prior to Sales; Label Specifies Emissions Performance and Efficiency
Strategy #4	Strategy #3, with 33% Tax Credit ($400.00)
Strategy #5	Testing/Rating by RWC Industry Trade Association
Strategy #6	Mandatory Weatherization of All Households
Strategy #7	Mandatory Weatherization Only for Households Installing New Stove/Furnace
Strategy #8	Firewood Moisture Content Controls
Strategy #9	Stove Sizing
Strategy #10	Encourage Larger Firewood Piece Size
Strategy #11	Require Underfire Air Source for New Fireplaces
Strategy #12	Episode Controls
Strategy #13	Research and Development of Improved RWC Appliances and/or Practices
Strategy #14	Encourage Alternative Fuels
Strategy #15	Periodic Inspection of RWC Equipment

This and similar frameworks for each WANT criteria are described below, in explaining how WANT criteria scores were assigned to each of the final fifteen strategies. The resulting WANT criteria scores are estimated in Table E2. The total scores in Table E2 constitute a preliminary ranking of the fifteen strategies.

This preliminary ranking becomes the final ranking, unless adjusted based on significant adverse consequences (risk factors) of implementation of strategies, determined as described in the next section. There were not such adjustments made to the preliminary ranking in Table E2.

The following twelve subsections describe the "satisfaction levels" used for each WANT criteria, to help assign scores to each strategy in a consistent manner. Accompanying notes describe examples of key considerations in assigning most scores.

A. WANT #1: Reduce RWC Emissions Per Household

This criteria reflects the degree to which strategy would (potentially) reduce RWC particulate emissions per household.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	Reduces RWC Emissions by >30%
Well	7-8	Reduces RWC Emissions by 10-30%
Moderately	4-6	Reduces RWC Emissions by 5-10%
Poorly	1-3	Reduces RWC Emissions by 0-5%
None	-0-	Reduces RWC Emissions by 0%

Scores under WANT criteria #1 were based on estimated emissions reductions achievable which are summarized in Table 7 (Section V) for most of the fifteen strategies. Only Strategies #1 and #2 afford >30% reductions in RWC emissions, and only after

TABLE E2
Keppner-Tregoe Scores for Final RWC Control Strategies
vs
All WANT Criteria and Risk Factors Assigned

WANT Criteria[1]	Weight Factor	Final RWC Control Strategies Selected for Evaluation																													
		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
1. Reduce RWC emissions per household	13	9	117	10	130	7	91	8	104	7	91	6	78	4	52	5	65	6	78	7	91	2	26	4	52	6	78	4	52	1	13
2. Reduce no. of RWC households	13	8	104	5	65	3	39	1	13	3	39	7	91	9	117	2	26	2	26	2	26	3	39	3	39	2	26	9	117	5	65
3. Widely applicable/effective	10	9	90	9	90	9	90	9	90	6	60	9	90	7	70	7	70	6	60	7	70	3	30	6	60	8	80	7	70	7	70
4. Maximize public acceptance	9	4	36	5	45	8	72	9	81	8	72	2	18	4	36	8	72	8	72	10	90	4	36	7	63	7	63	2	18	2	18
5. Discourage worst appliance/practice	9	8	72	9	81	3	27	5	45	3	27	2	18	2	18	5	45	7	63	5	45	4	36	5	45	7	63	7	63	7	63
6. Minimize consumer cost	6	3	18	8	72	7	42	8	48	7	42	4	24	6	36	8	48	9	54	10	60	6	36	8	48	6	36	8	48	5	30
7. Use proven technology	5	4	20	3	27	6	30	6	30	6	30	9	45	9	45	5	25	6	30	6	30	5	25	5	25	5	25	9	45	4	20
8. Minimize circumvention	4	6	24	9	36	2	8	4	16	2	8	7	28	3	12	2	8	4	16	6	24	5	20	3	12	5	20	7	28	4	16
9. Maximize agency feasibility	3	3	9	4	12	5	15	6	18	9	27	4	12	4	12	8	24	7	21	9	27	8	24	7	21	5	15	2	6	1	3
10. Encourage innovative technology	2	7	14	9	18	4	8	6	12	4	8	2	4	2	4	2	4	2	4	2	4	4	8	2	4	10	20	3	6	5	10
11. Minimize free market interference	2	1	2	3	6	7	14	5	10	8	16	2	4	2	4	5	10	8	16	10	20	5	10	5	10	7	14	1	2	7	14
12. Promote conservation and renewable resources	1	2	2	2	2	2	2	2	2	2	2	10	10	5	5	3	3	3	3	3	3	2	2	2	2	5	5	3	3	3	3
WANT Criteria Scores:		508		535		438		469		422		432		411		400		443		490		292		381		445		458		325	
Risk Factor Scores:		114		139		40		85		0		70		35		24		45		45		40		50		0		56		70	
Ranking		2		1		8		4		10		9		11		12		7		3		15		13		6		5		14	

[1] All MUST Criteria have been met.

2000 and 1995, respectively. Strategy #4 achieved 20% by the year 2000, and so scored 8. Strategies #3, #5, and #10 all scored 7, because their emissions reduction potential exceeded 10%. Strategies #6 and #9 had 7-10% emissions reduction, scoring 6. Strategy #13 also scored 6 because R&D is the key to the success of many of the best strategies, through development of test procedures, cleaner stoves, and better operating practices.

Scoring 4 were mandatory weatherization of only households installing a new stove (Strategy #7) and episode controls (#12). Strategy #14 (encourage alternative fuels) scored 4 because restricted wood supply restricts RWC, and because combustion of conventional fuels would emit less particulate.

B. WANT #2: Reduce the Number of RWC Households

This criteria should reflect whether a strategy would discourage new RWC households, or encouraging existing households to quit RWC.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	Strongly discourage new RWC households; or encourage existing RWC household to quit.
Well	7-8	Moderately discourage new RWC households; or existing RWC households to quit.
Moderately	4-6	Mildly discourage new RWC households; or encourage existing RWC households to quit.
Poorly	1-3	Little or no effect on number of RWC households.
None	-0-	Encourage new RWC households; or existing households to increase RWC.

Two strategies were considered most likely to strongly discourage new RWC households, or encourage existing households to reduce or quit RWC - weatherization of only those households installing new stoves (Strategy #7), and encouragement of alternative fuels (Strategy #14), primarily due to its restrictions on firewood supply. Close behind, scoring 8, was Strategy #1, whose restriction of stove sales to certified units, with no subsidy for purchase, could make new stove purchases costly enough to discourage new RWC households. Weatherization of all households scored 7, because lower heating requirements would make RWC less economically attractive vis a vis conventional fuel use for many persons who consider RWC a means of reducing their conventional fuel bills.

Strategy #2 could **mildly discourage new RWC households** because new stove purchases are limited to certified units, although the tax credit should keep the price reasonable. Required inspections of RWC households also could discourage people who would dislike this as an invasion of privacy, and not wish to be subject to possible mandatory maintenance costs or civil penalty. All other strategies were judged to have little or no effect.

C. WANT #3: Widely Applicable or Particularly Effective

This criteria reflects whether strategy would influence a high percentage of RWC appliances or practices, or strongly influence a major segment of them.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	Applies to all or most RWC appliances or practices.
Well	7-8	Applies to many RWC appliances and/or practices.
Moderately	4-6	Applies to significant fraction of RWC appliance or practice categories.
Poorly	1-3	Applies only to a few RWC appliances or practices.
None	-0-	No effect, not applicable to.

All strategies scored 6 or higher except Strategy #11, which applies only to new fireplaces. Strategies #1 - #4 all scored 9 because they would affect every stove/furnace sold, neglecting circumvention. Strategy #5 was considered less applicable because Trade Associations might not require all manufacturers to participate. Mandatory weatherization of all households (Strategy #6) affects existing as well as new RWC households, and is obviously more widely applicable than Strategy #7. R&D (Strategy #13) would affect many of the leading strategies themselves. Moisture controls (Strategy #8) potentially affects all RWC households and both stoves and fireplaces, but reliance upon voluntary compliance will reduce its effect. Benefits of encouraging larger piece size (Strategy #10) do not extend to fireplaces. Inspection (Strategy #15) affects only households with stoves. Encouraging alternative fuels might not affect households with assumed wood supplies. Stove sizing (Strategy #9) would eventually affect many households, after many years. Episode controls applicability is diminished by its voluntary nature.

D. WANT #4: Maximize Public Acceptance

The intent of this criteria is to reflect acceptability to the general public and second to acknowledge significant support or opposition.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	Fully acceptable; some significant support; no significant opposition.
Well	7-8	Acceptable to most parties; some support; no significant opposition.
Moderately	4-6	Lukewarm acceptance; most people don't know or care; or, offsetting support and opposition.
Poorly	1-3	Acceptable primarily to environmentalists; average person wary or opposes.
None	-0-	Not acceptable to many; strong opposition.

Likely public acceptance was deemed highest for Strategy #10 (piece size), since it offered significant potential benefits, at no cost, and with less work (less splitting of wood). Testing/labeling plus tax credit (Strategy #4) scored 9, because consumer options are not limited, but better consumer information is given, along with an optional subsidy for purchasing cleaner stoves. The other two labeling type strategies (#3, #5) also preserve all consumer options. Moisture controls (#8) and stove sizing (#9) also offer benefits with relatively little inconvenience or costs (down sizing average stove size should save on costs of equipment). Episode controls (#12) at least on a voluntary basis, and R&D (#13) also were considered relatively easy to win public support.

Restricting the public's choice of stoves (Strategies #1 and #2) will not likely be popular, but proponents should partially offset opponents. Mandatory weatherization of new RWC households (Strategy #6) won't be widely popular, but will similarly have some strong proponents. Requiring underfire air for new fireplaces would affect home builders, but most of the public would be relatively insulated from its effect since it 1) only applies to new units, and 2) costs would be rolled in with entire costs of a new dwelling. Mandatory weatherization of all households will affect far more people and be significantly less acceptable to the average person because it is a substantial mandated cost. Strategy #14 will be unpopular for restricting firewood supplies and was scored 2. Strategy #15 also scored this becasue it required entry into private homes, and potential required maintenance costs or civil penalties will be unwanted.

E. WANT #5: Discourage Worst RWC Appliances/Practices

This criteria seeks to reflect how much a strategy would discourage high emitting RWC appliances or poor RWC practices.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	Effectively eliminate all worst appliances or practices.
Well	7-8	Significantly discourages a substantial percentage of poor RWC appliances or practices.
Moderately	4-6	Discourages some poor appliances or practices.
Poorly	1-3	Little effect.
None	-0-	Encourages (if inadvertently) poorer RWC appliances or practices; or, no effect at all.

Strategies #1 and #2 which restrict consumer choices to certified stoves/furnaces most strongly discourage continued installation of "dirtier" burning units. The subsidy in Strategy #2 enhances this effect. R&D to improve RWC appliances/practices works directly to change poorer equipment/techniques by obtaining needed knowledge (Strategy #13). Periodic inspection (Strategy #15) would detect poorly operating burning units and require maintenance - the only strategy directly enforcing good RWC practices in the home. Strategy #14 discourages all RWC by restricting wood supply, and by encouraging conventional fuel use. Strategy #9 discourages larger stoves which tend to have higher emissions.

Labeling strategies (#3, #5) do not limit consumer choices to the cleaner burning units, although a tax credit (#4) would help achieve this result. Moisture control (#8) tends to discourage inadequate seasoning of firewood, but is voluntary. Likewise, encouraging larger firewood piece size in stoves (fireplaces not affected) is too discretionary to have a major discouraging influence on poorer practices. Episode controls (#12) are voluntary, and emphasize temporary cessation of RWC rather than improving one's RWC equipment, although public education on proper RWC methods helps discourage poor ones. Underfire air sources affect only small fraction of RWC situations (new fireplaces). Weatherization has relatively little effect on worst practices or units.

F. WANT #6: Minimize Consumer Cost

This criteria is to reflect how well a strategy would minimize any RWC costs (fuel, equipment, O&M, pass through costs from manufacturer or retailer, etc.). Such costs also may be offset by subsidies in some strategies.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	No added costs for consumers; or reduced costs.
Well	7-8	Low costs to affected RWC households.
Moderately	4-6	Significant costs to only a few RWC households.
Poorly	1-3	Significant costs to a significant number of RWC households.
None	-0-	Substantial added costs for RWC households ($1000s).

Encouraging larger firewood piece size (Strategy #10) scores 10 because it has no dollar or inconvenience costs to consumers (costs of public information desemination are very small, tax payer costs). Downsizing stoves (#9) reduces average stove costs. Encouraging alternative fuels (#14) by lowering conventional fuel costs provides lower cost alternative for RWC households which face higher firewood costs due to restricting firewood supplies. Moisture control (#8) and episode controls (#12) are cheap. Labeling strategies (#3, #5) preserve options to buy cheaper units; subsidy option (#4) potentially reduces consumer costs. Limited weatherization (#7) is less costly than the more widely applicable case (#6).

Limiting consumer choice to certified stoves (#1, #2) should increase average stove costs, perhaps significantly.

G. WANT #7: Use Proven Technology

This criteria reflects whether a strategy's technology is proven for this application; has low O&M problems; needs no R&D.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	All technology required is fully proven, in some application or use.
Well	7-8	Technology fully proven, but only for a different use.
Moderately	4-6	Technology assumed sound, but untested; or not applicable because no technology is involved.
Poorly	1-3	Possible problems with technology anticipated.
None	-0-	Technology problems likely; risky.

Weatherization (#6, #7) and conventional fuel use (#14) are fully proven technologies. Downsizing stoves (#9) and encouraging larger firewood piece size (#10) require no new technology. Testing/labeling strategies (#3, #5) do not limit allowable stove emissions, and so will not necessarily favor newer (less proven) technology, as will Strategies #1 and #2. Moisture control (#8) and episode controls (#12) do not rely on any technology. Underfire air (#11) technology is assumed sound but not well documented by research to date. R&D (#13) improves proven technology over time, as well as finds new technology.

H. WANT #8: Minimize Circumvention

This criteria is to reflect ease of non-compliance (or non-response) to strategy's objectives.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	No circumvention occurs
Well	7-8	Difficult to circumvent, so little occurs; perhaps due to good enforcement.
Moderately	4-6	Not too easily circumvented; little incentive to do so.
Poorly	1-3	Relatively easy to circumvent, but probability not high.
None	-0-	Easily circumvented; high probability of occurrence.

For Testing strategies (#1 - #4) scores are proportional to assumed percent coverage - e.g., 90% for Strategy #2. The "carrot and stick" of Strategy #2 ranked highest because of the control of stove sales coupled with the incentive to purchase the certified units. Tax credit costs were not considered a major problem because the State of Oregon has had pollution control tax credits for industry for years. Oregon could reallocate some of these pollution control expenditures to RWC, which has surpassed industry in total particulate emissions in Portland. Weatherization of all households (#6), enforced through utility service change, was considered much more enforceable than weatherization limited to households purchasing new stoves (#7) enforced via building codes and installation permits. Building permits were considered much easier to circumvent. The inclination to circumvent would be higher for the homes singled out for this requirement. Strategy #14 with its subsidies for conventional fuels and firewood restrictions would encourage the use of different fuels. Piece size (#10) produces no incentive to circumvent, nor do underfire air (#11) or R&D (#13). Other strategies have one or more elements that are fairly easily circumvented.

I. WANT #9: Maximize Agency Feasibility

This criteria reflects strategy's likelihood of minimizing major agency problems such as costs, lack of authority, or political opposition.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	"Cheap" and easy to implement, and to document results; affected parties cooperate.
Well	7-8	Only minor administrative problems.
Moderately	4-6	Minor problems certain; major problems possible but thought to be avoidable.
Poorly	1-3	At least one major administrative problem (cost, authority, politics) likely to block or postpone implementation.
None	-0-	Too difficult (or expensive) to implement, or to obtain needed legal authority; and strong political opposition.

Highest scores (9) go to encouraging larger piece size (Strategy #10) because it is so easy to implement, and Strategy #5 because the private sector implements it. Underfire fireplace air (#11) and moisture control (#8) present agencies with little work, few problems. Stove sizing (#9) and episode controls (#12) offer only minor administrative problems. Somewhat greater problems occur in implementing R&D (funding problems), and mandatory testing/labeling (#3, #4). Inspection of RWC households (#15) could face major public opposition and in Oregon legal prohibition against regulating residential heating as an air pollution source. Major problems with Strategy #14 include limiting access of public to public lands, and possibly political flak for subsidizing conventional fuels.

J. WANT # 10: Encourage Innovative Technology

This criteria reflects strategy's likelihood of using, or fostering the development of innovative technological approaches.

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	Major commitment to innovation; or encourages it through subsidy.
Well	7-8	Significantly encourages innovation.
Moderately	4-6	Mildly encourages innovation.
Poorly	1-3	Doesn't discourage innovation, but not likely to have much effect.
None	-0-	Discourages innovation; favors conservative approaches.

R&D (Strategy #13) easily scores 10. Requiring (#7, #9) and subsidizing with tax credits (#9), the purchase of cleaner burning stoves, is a major encouragement of innovation in stove design. Except for subsizing cleaner labeled stoves (#4), all other strategies only mildly encourage innovation, if at all.

K. WANT #11: Minimize Free Market Interference

This criteria reflects strategy's non-interference in free market supply, demand, or pricing of goods. Use of market mechanisms, or incentives/disincentives to regulate RWC is scored low unless favored by private sector - e.g., voluntary regulation by Trade Association. Promotion of better educated consumer choice, scores high (enhances market).

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	No interference with supply/demand or prices related to RWC.
Well	7-8	Strongly promotes better consumer choice.
Moderately	4-6	Moderately enhances consumer information, but may not affect consumer behavior very much.
Poorly	1-3	Little or no effect on price or consumer choice.
None	-0-	Direct interference with price, or supply/demand and which is not accepted/sanctioned by private sector.

Encouraging larger firewood piece size (Strategy #10) has no interference with market forces. Encouraging downsizing of stoves (#9) places larger units at some disadvantage, but this is far from direct interference. The testing/labeling strategy (#5) is implemented by the private sector itself. R&D (#13), and labeling without limiting which stoves can be sold (#3, #4) enhance market activity by promoting better informed consumer choice. Tax credit subsidies (#2, #4) directly interfere with market prices. Mandatory weatherization indirectly interferes by tying up significant funds that could be spent on other projects and by creating a market for weatherization which competes with the conventional fuel market. Encouraging conventional fuels through lower rates and restricting wood supply, doubly interferes as well as benefiting industrial users of wood residues.

L. WANT #12: Promote Conservation and Renewable Resources

This criteria reflects strategy's likelihood to directly or indirectly encourage conservation of energy, or use of renewable resources (except wood for RWC).

Satisfaction Level	Possible Points	Conditions for Satisfying This Level
Fully	9-10	Strongly promotes conservation and renewable resources.
Well	7-8	Significantly encourages conservation and renewable resources.
Moderately	4-6	Moderately encourages conservation and renewable resources.
Poorly	1-3	Little or no effect.
None	-0-	Discourages conservation or encourages use of conventional fuels (oil, gas, electricity).

Weatherization (#6, #7) directly encourages conservation of energy, but much less so in the case of limited mandatory weatherization (#7). Aside from R&D, which can strive to develop RWC appliances/practices which conserve energy, all other strategies have little or no effect.

III. RISK FACTORS

Table E2 summarizes the WANT criteria scores and the preliminary ranking they provide among the fifteen final control strategies. Table E2 also shows the risk factor scores assigned to represent major potential adverse consequences of implementing a strategy. These adverse consequences scores are summarized in Figure E1 and discussed in this section. Risk factors were discussed in Section III D of the text.

The adverse consequences listed in Figure E1 were those considered most likely to block or limit the effectiveness of a strategy. In many cases, the risk factors represent the possible failure of key assumptions to come true, which would undermine the strategy in significant ways - e.g., the failure of the RWC industry to commercialize

FIGURE E1

Potential Adverse Consequences (Risk Factors) of Implementing Final Fifteen RWC Control Strategies

Potential Adverse Consequences of Implementation	Probability of Occurrence (P)	Seriousness of Impact (S)	Risk Factor (P x S)
Strategy #1: (Testing/Certification)			
- Industry may not produce a stove emitting ≤5 g/kg for ≤$1200.	3	8	24
- Public opposition to units on freedom of choice in stove purchases.	5	8	40
- Inability to obtain legal authority to prohibit sales/installation of non-certified units (at least in Oregon where ORS 468.290(5) exempts residential space heating from regulation).	5	10	50
			114
Strategy #2: (Testing/Certification, tax credit)			
- Lack of funds for subsidy (General Fund strapped) industry oppose tax credit shift?	5	10	50
- Industry doesn't provide a stove which emits ≤5 g/kg for ≤$1200.	3	8	24
- Legal authority to prohibit sales not obtainable.	5	10	50
- Public opposition to freedom of choice in stove purchases.	3	5	15
			139
Strategy #3: (Testing/Labeling)			
- Inability to obtain legal authority to require testing and prohibit sales of non-labeled units.	4	10	40

P = Probability of Occurrence (1 to 10)

S = Seriousness of Impact (1 to 10)

Risk Factor (PxS) (10x10 = unavoidable disaster)

FIGURE E1 (Cont.)

Potential Adverse Consequences of Implementation	Probability of Occurrence (P)	Seriousness of Impact (S)	Risk Factor (P x S)
Strategy #4: (Testing/Labeling, tax credit)			
- Lack of funds for subsidy (tax credit)	5	6	30
- Industry cannot produce a stove which emits 5 g/kg for $1200.	3	5	15
- Inability to obtain legal authority to require testing and prohibit sales.	4	10	40
			85
Strategy #5: (Testing/Rating, by Industry)			
- None	0	0	-0-
Strategy #6: (Weatherization, all households)			
- Public acceptance (Voter approval) of mandatory weatherization may not be obtained.	5	8	40
- Adequate financing may not be available.	3	10	30
			70
Strategy #7: (Weatherization, only certain households)			
- Public acceptance of limited mandatory weatherization could be much worse but affected group is smaller.	5	5	25
- Adequate attractive financing may not be available.	1	10	10
			35
Strategy #8: (Moisture Control)			
- Limited research to date means estimated benefits may not be realizable as estimated.	4	6	24

P = Probability of Occurrence (1 to 10)

S = Seriousness of Impact (1 to 10)

Risk Factor (PxS) (10x10 = unavoidable disaster)

FIGURE E1 (Cont.)

Potential Adverse Consequences of Implementation	Probability of Occurrence (P)	Seriousness of Impact (S)	Risk Factor (P x S)
Strategy #9: (Sizing)			
- Limited research means estimated benefits may not be realizable as estimated.	5	9	45
Strategy #10: (Piece Size)			
- Limited research means estimated benefits may not be realizable as estimated.	5	9	45
Strategy #11: (Fireplace Underfire Air)			
- Limited research (one test) means estimated benefits may not be realizable as estimated.	5	8	40
Strategy #12: (Episode Controls)			
- Legal authority for mandatory curtailment may not materialize, limiting program to voluntary approach.	5	10	50
Strategy #13: (Research & Development)			
- None	0	0	-0-
Strategy #14: (Encouraging Alternative Fuels)			
- Public acceptance of limiting of wood supply unlikely.	7	8	56
Strategy #15: (Inspections)			
- Legal authority for inspections may not materialize (especially in Oregon).	7	10	70

a stove which emits 5 g/kg and costs $1200.00, by about 1984. This assumption underlies Strategies #1 - #4. If it did not come true, Strategies #1 and #2 would be affected most because they limit consumer choice to stoves which emit $\leq$5 g/kg. The labeling strategy with a tax credit for such clean units (#4) also would be undermined, but less seriously, because it does not limit consumer choices to only such clean units. The probability that such a clean commercial unit will not be available is not considered great, because of promising reports of several stoves that already approach these specifications (see Appendix D, Section A).

Some of the larger risk factors represent the possibility that critical legal authority or funding will not be obtainable. Appropriate legal authority was considered especially critical: 1) to require testing and limit commercial sales of non-certified (#1, #2) or non-labeled (#3, #4) stoves; 2) for mandatory episode controls (#12), and 3) to require household inspections (#15). Funding was considered critical to the success of weatherization (#6, #7) and tax credits (#2, #4). Adequate public acceptance was considered particularly critical and not at all assured, for mandatory weatherization (#6, #7); for testing/certification strategies (#1, #2) which dramatically limit the choice of stoves available for purchase; and for the limitation of firewood supplied from public lands in order to help encourage alternative fuels (#14).

For several strategies key assumptions were based on very limited data from the literature. In such cases, if further research failed to provide confirmation, the estimated RWC emission reductions might not actually be realizable. This was considered particularly true for strategies involving charging larger pieces of firewood (#10), reducing average stove size (#9), and fireplace underfire air (#11); and to a lesser extent, for moisture control (#8).

For two strategies (#5, #13), no adverse consequences were identified.

For each strategy, the total points assigned for risk factors in Figure E1 was compared in Table E2 with the total WANT criteria scores. These two scores were not substracted, but their relative magnitudes were compared to consider whether the preliminary ranking based on WANT criteria scores should be altered due to potential adverse consequences of implementing any strategy.

The two top ranked strategies (#1 and #2) also had the two highest adverse consequences scores; and the fourth ranked strategy had the next highest risk factor. The major risk factors involved possible problems in obtaining legal authority to require testing and to restrict commercial sale of non-certified or non-labeled stoves. In depth analysis of barriers to enactment of such legal authority was beyond the scope of this report.

However, precedent exists for such legal authority in control programs implemented in Britain, New Zealand, and West Germany (see Section II A, B, and C); and in the program adopted in Medford, Oregon (see Section II E), which urged development of a state certification/testing program. Precedent also exists for state tax credits for industrial pollution controls - e.g., in Oregon.[32] For Portland, Oregon, RWC particulate emissions are estimated to equal or surpass industrial particulate emissions (in tons/year), and are potentially more hazardous to public health since the emissions are released in sensitive population areas. Thus, in Oregon at least, a strong argument can be made for simply reallocating pollution control tax credits from industrial to RWC controls.

Thus, because the potential emissions reductions are significantly greater for Strategies #1 and #2, and major risk factors seem surmountable, no change was made in the preliminary ranking of these top rated strategies.

No compelling reasons were found to alter the other rankings either, so the initial WANT criteria ranking became the final ranking also. Several observations about the relative rankings seem noteworthy, however. For example, R&D (Strategy #3) ranked high (6th) and had no adverse consequences. Its benefits are speculative by nature, however, and R&D funding is scarce under present economic conditions.

Several strategies which rank fairly high - e.g., promoting larger firewood piece size (#10) and smaller stoves (#9) - did so in part because they don't present many problems, but they are based on very thin research results. These strategy approaches are prime candidates for future research.

APPENDIX F

Selected Costs and Benefits of Final RWC Control Strategies

This appendix estimates selected dollar costs assumed to be associated with implementation of fourteen of the fifteen final RWC Control Strategies selected in Section VI for final evaluation and ranking. It also describes selected benefits in narrative terms for each strategy. No dollar costs were estimated for Strategy #14, which called for encouraging fuel alternatives to RWC.

I. STRATEGY #1: NEW/REPLACEMENT STOVES MUST BE TESTED AND CERTIFIED TO EMIT LESS THAN 5 G TSP/KG WOOD BEFORE SALE OR INSTALLATION IS ALLOWED

A. Costs

The costs of an emissions testing program are addressed in this section in four major categories:

- •Costs per stove model tested
- •Test procedure development
- •Administrative costs
- •Per stove costs

This information applies to Strategies #1 - #5, all of which involve testing of all or most stoves/furnaces marketed.

Costs Per Stove Model Tested

Costs of conducting the actual emission tests can be estimated in a variety of different ways, depending on which test method is assumed. In order to develop a single best estimate, four different procedures are discussed below.

1. EPA Method 5 Plus Back-half Catch (Oregon Method 7)[29]

Under Task 5 of this contract, 19 stove tests were conducted at a cost of about $50,000 which averages to about $2,600 per test. Determination of efficiency by the stack loss method also was included within these costs. If an emissions rating program were established, some range of operating conditions would need to be tested rather than one single burn rate, since emission factors generally vary significantly with burn rate. Testing four different burn rates probably would be sufficient to characterize emissions over a range of conditions, while still allowing any serious test procedure error to be identified. Without economies of scale, four separate tests would thus be estimated to cost about $10,000. With the economies of repetitive testing on multiple stoves, a cost of about $5,000 - $7,500 seems a reasonable estimate for testing particulate emissions at four different burn rates by this method.

2. Efficiency Testing by Calorimeter Room and Stack Loss Method

Shelton Energy Research of Sante Fe, New Mexico currently tests stove efficiency by this method for about $5,400 per stove.[45] This includes six different tests at low to high burn rates to characterize performance over the range of operating conditions. Combustion efficiency determination is included in this procedure. This also would provide other options for structuring certification requirements. For example, rather than setting an emission limit of 5 g/kg, some minimum combustion efficiency could be required with the certification program essentially the same in all other respects.

3. British Electrostatic Precipitator Method

British law requires stoves to meet certain emission limits in order to be installed in Smoke Control Areas.[1f,1h] Testing is conducted by the British Coal Board (NCB) using an electrostatic precipitator method.[1f,1h] Using this method the NCB estimates the costs of testing one stove to be $2,400, which includes 5 tests at each of three burning rates (low, medium, and high).[1f] While this test is not necessarily applicable to wood stoves because of its questionable capture efficiency for volatiles, it does illustrate a comprehensive testing program in actual operation.

4. New Method-Combustion Efficiency Measurement Using Catalysts

These authors **conclude** that one of the least expensive test methods likely to be developed and commercialized involves the use of catalysts to determine an emission factor in the form of grams of unburned carbon per kg wood. This method would involve complete combustion of some known fraction of the stack gas via a catalyst with known amounts of oxygen supplied to ensure complete combustion. Measurement of CO_2 concentrations before and behind the catalyst, stack flow measurements, and determination of the amount of wood burned also would be required. Both CO and particulate emissions are of concern, and this method would sidestep issues of how much of the carbon was in one form or the other. Shelton estimates[45] that costs for conducting such a test for four different burn rates might ultimately be reduced to about $2,000.

5. Single Estimate of Model Testing Costs

The arithmetic average of these four possible evaluation procedures (each including multiple tests) is $4,400

[(2000 + 2600 + 5400 + 7500)/4 = 4375]. This value is selected as the best single estimate of costs per model tested for emissions.

Test Procedure Development

In order to document the acceptability and validity of whatever emissions testing method is selected, it is arbitrarily assumed that about $50,000 in research contracts or expenses would be required. This, for example, would allow four stoves to be tested five times by the Oregon Method 7 procedures (@$2,500 per test).

Administrative Costs

If it is assumed that about 30 new stove models would be tested each year, at an estimated $4,400 cost per stove tested, this would result in $130,000/year allocated for testing costs. If it is assumed this program would require two professionals and one half-time secretarial position for testing and report-writing activities at a $30,000/year average loaded rate, these labor expenses would total $75,000 per year.

This would leave a remainder of $55,000 per year for rent ($15,000/year), wood acquisition and standardization costs ($5,000/year), printing ($5,000/year) and amortized equipment purchase ($30,000/year), which appears reasonable.

Allocation of one-half professional person for enforcement activities and one-half professional person for education and public relations activities would add about $30,000/year for annualized costs of $160,000/year. Charging manufacturers $1,000 each to test/certify each stove, could recoup $30,000 under these assumptions, reducing total administrative costs to $130,000.

Per Stove Costs

Administrative costs of this program per stove are estimated for jurisdictions with annual stove sales of 5,000 to 10,000 and 20,000 in this section. After the research expenditure of $50,000 to establish and verify the test procedures, the $130,000 annual operating expenses would result in costs to the government per stove sold of $26, $13, or $6.50 for these three cases. The costs of attaching a label which specifies emission rates and/or efficiency is estimated at $5.00 per stove (labor and manufacturing costs), bring administrative costs per stove to $31, $18, and $12 respectively. This $5.00 labeling cost was assumed to apply to Strategies #1 - #5. Since Strategy #1 is assumed to assume only that 60% of stoves purchased are certified, the administrative costs per "affected" stove are $52, $30, and $20 respectively. Research and tax credit costs are not included in these per stove costs.

B. Benefits

Analysis in Section V A 1 estimates the emission reduction attributable to this strategy as **8% by 1990 and 30% by 2000.** Thus, the emissions reduction benefits accumulate over time significantly, as more and more new and/or replacement burning units are installed, 60% of which are assumed to be the cleaner, certified types.

II. STRATEGY #2: NEW/REPLACEMENT STOVES MUST BE TESTED AND CERTIFIED TO EMIT LESS THAN 5 G TSP/KG WOOD BEFORE SALE OR INSTALLATION IS ALLOWED; PLUS $400/STOVE TAX CREDIT

Strategy #2 would employ the same staff and facilities, and is assumed to have the same base costs as Strategy #1 ($130,000 per year administrative costs, plus $50,000 one-time research costs to develop test procedures), plus tax credit costs. Tax credit costs (tax revenues foregone) were estimated assuming a percent coverage of 90% for Strategy #2 - i.e., that 90% of new units would be certified and hence eligible for the tax credit. For annual sales of 5,000, 10,000, and 20,000 units, this results in annual tax credit costs of $1.8 - $7.2 million.

Additional administrative costs to add the tax credit program were based on one additional full-time clerical person plus secretarial support ($30,000 per year assumed). This increases annual administrative costs for Strategy #2 to $160,000 per year. This results in annual administrative costs for Strategy #2 - for the three annual sales levels above - of $36, $18, and $9 respectively, per "affected" (certified) stove.

B. Benefits

In Section V A 1, the potential particulate emission reduction achievable by this strategy, at its assumed 90% coverage **are 11% by 1990 and 39% by 2000.** This is the highest emissions reduction achieved by any of the fifteen strategies evaluated.

III. STRATEGY #3: TESTING AS BASIS FOR MANDATORY LABELING PRIOR TO SALES

A. Costs

All costs of this program are essentially the same as for Strategy #1. However, costs per certified stove purchased (administrative costs per affected stove/furnace) are three times as high, since this strategy is assumed to result in only 20% of the stoves purchased being certified units compared to 60% for Strategy #1.

B. Benefits

Based on analysis presented in summary form in Section V A 1 and detailed form in Appendix D, this strategy is assumed to result in 3% emission reduction benefit by 1990 and a 11% emission reduction benefit by 2000.

IV. STRATEGY #4: TESTING AS BASIS FOR MANDATORY LABELING PRIOR TO SALES, PLUS $400/STOVE TAX CREDIT

A. Costs

Costs of initial research, and annual administrative costs for this program are essentially the same as for Strategy #2. However, costs per certified stove purchased are 2.25 times as high, since Strategy #4 is assumed to effect only 40% of the stoves purchased per year versus the 90% for Strategy #2. This also affects the tax credit costs for the three sales volumes considered (5,000, 10,000, and 20,000 sale per year), because only 40% of the units purchased would be eligible for tax credits. This results in annual tax credit costs of $0.8 - $3.2 million.

B. Benefits

Based on analysis presented in Section V A 1 and Appendix D, this strategy is assumed to result in an 5% emission reduction benefit by 1990 and a 21% benefit by 2000.

V. STRATEGY #5: TESTING/RATING BY RWC INDUSTRY TRADE ASSOCIATION

A. Costs

This strategy's costs would be essentially the same as for Strategy #3 (#1), but with the RWC industry instead of government implementing it. A significant difference in distribution or pass through of costs to the public would exist, however.

If industry passed on to the consumer the per-stove administrative costs identified for Strategy #3 ($12-31 per unit), then purchasers of new wood stoves would pay for this strategy. Under Strategies #1 - #4, government pays all costs which are thus effectively distributed over all taxpayers. Average taxpayer costs would range from a few pennies per year for Strategies #1 and #3 to $5-10 or more per year for Strategy #2 involving the tax credit costs. However, since total particulate emissions from RWC in areas like Portland, Oregon rival or surpass total emissions from all other industry[4], states (like Oregon) which offer substantial industrial tax credits for pollution abatement, may want to adjust their tax credit program to accommodate the RWC source.

VI. STRATEGY #6: WEATHERIZATION OF ALL HOUSEHOLDS IN AN AREA

A. Costs

Pacific Power and Light estimates that weatherization of a typical household in the Portland metropolitan area costs about $1,400 to $1,500 per household.[46] This includes such activities as roof and floor insulation, addition of storm windows, and caulking and weather stripping. For an area in which 60% of households can be characterized as "poorly weatherized"[37] this results in average weatherization costs of about $900 for each household in a metropolitan area ($1,500 * .6 = $900). For metropolitan areas with 100,000 or 300,000 households, this would require investment of $90 million or $270 million.

Estimated administrative costs for a mandatory weatherization program assumed 5,000 to 20,000 households weatherized per year. Assuming administrative costs of $30.00/household, affords annual administrative costs of $150,000 - $600,000. Assuming weatherization of poorly weatherized RWC households is accomplished in 10 years, starting in 1985, the full 7% emissions reduction would be achieved by 1995. For Strategy #7 (weatherization of households installing new/replacement stoves), a

10-year average stove life was assumed (10% annual replacement rate for existing stoves). This also results in full weatherization benefits within 10 years. Assuming RWC households are 10% of all households, annual administrative costs could range from $20,000 - $80,000 per year.

B. Benefits

In the short-term, weatherization of 60% of an area's households such that heating requirements are reduced by 40% is estimated to reduce RWC emissions by 1995 by about 7% (see Section V B 1). However, most weatherization programs incorporate only cost-effective conservation actions, with a 5 year or less payback. Thus it can be argued that the weatherization programs "pay for themselves" in ultimate fuel savings, with emission reduction a side benefit.

VII. STRATEGY #7: MANDATORY WEATHERIZATION ONLY FOR HOUSEHOLDS INSTALLING NEW WOOD STOVES/FURNACES

A. Costs

For an area with 100,000 households in which either 10% or 20% of households are projected to buy new or replacement stoves between 1985 and 2000, weatherization costs over that time period at $1,500 per household would equal $15 million or $30 million.

B. Benefits

If all households were to cooperate with this strategy and not circumvent the requirements by installing stoves without "permits", the emission reduction benefits would equal those (7%) of Strategy #6, but with less weatherization investment

costs. However, more circumvention would probably occur; 30% more was assumed by 1992 (3.5%) reducing emissions reduction benefits by this amount to 5% by 1995. The extent of circumvention would depend on the financial burden involved, which could be mitigated by attractive financing terms (no or low interest loans), and whether the requirement is accepted as equitable.

VIII. STRATEGY #8: FIREWOOD MOISTURE CONTROL

Strategies 8, 9, and 10 are all public education strategies, and thus could all be incorporated within a comprehensive public education strategy. Costs presented in this section can be considered to cover Strategies 8, 9, and 10 in combination. It also was assumed that implementation of any one strategy would cost half as much ($45,000) as implementing all three ($90,000).

In order to achieve the emission reduction benefits cited for these strategies in Section V B 2, it is assumed that the following administrative and materials costs would be incurred.

Agency Information Officer

One full-time professional ($30,000) could communicate the desired changes in operating practices to the general public by making 100 talks/presentations per year, and managing the development of media materials.

Television and Radio Spots

Once prepared, video and radio spots likely would receive free airtime for presentation to the general public, as did six video spots on wood heating practices in 1981 in Oregon.[47] The Northwest Power Council funded the development of six low-budget, still-picture video spots on wood heating practices in 1981. It is assumed that a similar $50,000 expenditure could produce three or four higher quality spots on optimum operating practices to reduce emissions, and that these spots would receive free air-time.

Printed Materials

Artwork, typesetting, and printing costs are estimated at $1,800 for production of 20,000 copies of a three-fold/page brochure. Producing 100,000 copies per year would thus be estimated to cost less than $9,000/year.

B. Benefits

Educational programs to promote the better drying of wood were estimated to be able to reduce emissions by 6.2% in Section V B 2.

IX. STRATEGY #9: STOVE SIZING

A. Costs

Costs for an educational program on this subject were discussed under Strategy #8 above.

B. Benefits

Educational programs to promote stove "downsizing" were estimated (Section V C 1) to be able to reduce emissions by 7% by 1990 and 10-11% by 2000.

X. STRATEGY #10: ENCOURAGING LARGER PIECE SIZE

A. Costs

Costs for an educational program on this subject were discussed under Strategy #8 above.

B. Benefits

Educational programs to encourage the use of larger pieces of wood were estimated to be able to reduce emissions by 11.5% in Section V C 2.

XI. STRATEGY #11: REQUIRE FIREPLACES TO HAVE AN UNDERFIRE AIR SOURCE

A. Costs

The addition of an underfire air-device to an existing fireplace is estimated to cost about $100 per installation. A household which burns 1.5 cords of wood per year, has an estimated TSP emissions of 52 lbs/year (1.5 cords x 1.75 tons wood/cord x .01 tons TSP/ton wood x 2000 lbs = 52.5 lbs TSP/year). Underfire air was estimated to reduce emissions by 20% (Section V A 3). This translates to a control cost of $9.50 per pound TSP, or $19,000 per ton. This compares to one recent estimate of control costs for industrial particulate sources of about $10,000 per ton.[33] On an annual basis, for an area in which 1000 to 3000 new fireplaces were installed, adding underfire air systems to these units would result in incremental costs of $100,000 to $300,000 per year.

B. Benefits

Based on the analysis in Appendix D 1 c this strategy is assumed to reduce year 2000 emissions by 2%. Reductions by 1990 would be estimated to be less than half of that, or about 1%.

XII. STRATEGY #12: EPISODE CONTROLS

A. Costs

Establishing a voluntary episode control program under which wood burning households are requested not to burn wood (unless it is the sole heat source) should cost about $25,000 in initial investment and $8,000 in annual operating costs. These costs estimates are derived largely from experience gained with the episode control program in operation in Missoula, MT.[22]

Initial Investment Costs Estimated at $25,000

- Automatic Particle Monitor, for real time particulate monitoring costs about $15,000.
- The Missoula Air Pollution Control Agency spent $13,000 for peripheral computer equipment to provide access to the state agency's air quality computer. This equipment provided other benefits such as word processing, printing, and modelling capability, so costs allocable to the data aquisition system are arbitrarily assumed to be $10,000.

Annual Operating Costs Estimated at $8,000

- 30% of one professional's time is required over 5 winter months to coordinate the Missoula system. Based on an assumed loaded salary cost of $30,000 per year, this costs $3,700 ($30,000 X 5/12 X .3 = $3,700).
- Equipment maintenance/repair costs estimated at 10% of investment cost per year or $2,500.
- Phone system with recorded messages on air quality status costs are about $1,150 per year.
- Miscellaneous costs of $650/year would result in total annual operating costs of $8,000.

B. Benefits

The chief benefit of this strategy is emissions reductions on worst air quality days, estimated at 33% for RWC emissions on worst air quality days in Section V B 3.

XIII. STRATEGY #13: RESEARCH AND DEVELOPMENT OF IMPROVED RWC APPLIANCES OR PRACTICES

A. Costs

Costs for this broad category of research and development work depend clearly on the level of research undertaken and the degree of outside support. Possible costs for three of the more promising research areas are discussed below.

Private/Academic Research Contracts

$100,000 per year could be allocated to support the development of improved RWC appliances and practices, in a program similar to the "appropriate technology" support grants which some state governments fund. By limiting single grants to $10,000 and establishing a format for grant competition, new and innovative wood burning technology improvements could be encouraged.

Government Funded Emissions Test Facility

Testing program cost estimates were generated in the discussion of costs for Strategy #1. The annual operating costs for conducting tests of 30 burning units per year at about four operating conditions per unit, were estimated at $130,000 per year, including test equipment amortization. With a research and development focus, the program could include 15 device tests and 60 tests (15 x 4) to compare the benefits of alternate operating practices.

Awards for Development of Low Emitting Woodburning Units and Simplified Emission Tests

Two $50,000 awards could be offered for the development of 1) the first woodburning unit which emits less than 1 g/kg of particulate concurrent with an overall energy efficiency of 50% or greater and 2) a simplified emissions measurement technique with costs per burn cycle test of less than $200.

B. Benefits

No potential emissions reduction benefits could be estimated for this strategy because its results are by nature too uncertain.

However, with adequate funding R&D could be extremely valuable in promoting the advancements which are most needed in controlling RWC emissions - e.g., inexpensive, standardized emissions test methods/equipment, and better quantitative data on emissions under various burning conditions.

XIV. STRATEGY #14: ENCOURAGING CONVENTIONAL AND ALTERNATE FUELS

A. Costs

No costs were estimated for this strategy because the activities involved could not be well enough defined. The institutions involved already have programs which would be involved. Estimating their incremental costs to do what this strategy calls for would be very difficult.

B. Benefits

Likewise, no emissions reduction benefits could be estimated. Benefits would include holding down utility costs of lower income people (lifeline rates), and promotion of renewable energy sources (solar). However, provisions for restricting wood supply would not be popular, benefiting only those who would become the recipients of this biomass for alternative uses.

XV. STRATEGY #15: PERIODIC INSPECTION OF RWC EQUIPMENT

A. Costs

For an inspector employed six months per year at a loaded cost of $15,000, and an inspection rate of six burning units per day, labor costs would be about $20 per inspection ($15,000/(6 units/day x 125 days) = $20/unit inspection). An assumed equipment and training cost of $3,750/year would increase costs per unit inspection to about $25 ($3,750/750 units per winter = $5). For an area in which 50,000 to 100,000 units were inspected per year, costs in the $.75 to $1.5 million range would result.

B. Benefits

The major benefit which would be achieved by such a program would be in improved fire safety. For example, 33% of all single family dwelling fires in Oregon are associated with solid fuel burning equipment.[25] If an inspection program were to reduce that 33% to 15% then an 18% reduction in total single family dwelling fires would occur. This will lower claims paid by fire insurance companies. If these savings are passed onto policyholders, and it the average household's fire insurance cost per year is $150, this 18% benefit would equal a $27 ($150 x .18 = $27) savings per household per year. This value is slightly in excess of the estimated annual costs of an inspection program. For an area in which 50,000 to 100,000 units were inspected per year, benefits in the $.75 to $1.5 million range would result.